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CONTENTS

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THE CONTROL OF CORROSION IN MARINISED GAS TURBINES

J. F. G. Condé, B.Sc., F.I.M., R.N.S.S.
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SYNOPSIS

The application of gas turbines in the Royal Navy in the period since 1947 is reviewed briefly and service experience in relation to salt accelerated hot corrosion is described. The nature of the corrosion effects which are encountered in the nozzles and turbine blades of marine gas turbines is indicated and the factors affecting such corrosion are summarised. Available information on the mechanism of corrosion is outlined and some relevant practical and theoretical consideration are discussed. Those measures already adopted to control the phenomenon are detailed and further potential techniques are enumerated and discussed. A comprehensive research and development programme is described which seeks to provide effective methods for controlling corrosion to enable the time between overhauls and turbine inlet temperatures to be increased safely and progressively. The ad hoc and fundamental elements of the R & D programme are described and include rig testing of existing and new alloys and coatings, engine testing of promising materials or coatings, basic studies of the mechanism of corrosion and the development of filtration techniques to reduce contamination levels in air and fuel.

Introduction

Historical Background

The potential advantages of gas turbine propulsion were quickly appreciated by the Royal Navy[1, 2] and in 1947 an MV Gatric engine was fitted in a MGB. This was followed by construction and trials ashore, and in small craft at sea, of a number of simple and complex cycle gas turbines. The first operational application of gas turbine propulsion was made in 1958 when BSE marine Proteus gas turbines went to sea in the *Brave* Class patrol boats. During the early 1960s a variety of types of gas turbine, ranging in rating from about 50 bhp to several thousand bhp were fitted in several classes of ship. These were to meet requirements ranging from portable fire pumps to electric power generation, and main boost engines in combined steam (Cosag) or diesel (Codag) and gas turbine propulsion systems. In the summer of 1968, H.M.S. *Exmouth* was commissioned and became the first major escort vessel to join the Fleet with entirely gas turbine main propulsion plant. Subsequently, it was stated that future policy would be to fit gas turbine main engines in all new major surface escort vessels.

Initially, the gas turbines fitted in operational ships were of semi-industrial type, being specifically designed and developed to meet the special requirements of the marine environment, resistance to shock loading, mechanical reliability and maintenance by Dockyard staff. By 1963 the reliability of the aircraft gas turbine in civil airline service had improved to the point where a life of 4,000 hours or more between major overhauls had been achieved. In addition, the high power/weight ratio, lightweight, compact nature, widespread use, availability in large units of power and low first-cost/h.p. (due to development costs being absorbed by aircraft engines) were attractive features. The high specific power could offer enhanced range by enabling a greater quantity of

TABLE 1. Characteristics of Gas Turbines in Service in the Royal Navy (2, 23)

Engine Type	*Application*	*Pressure Ratio*	*Max. Turbine Inlet Temp. °C*	*Normal Running Turbine Inlet Temp. °C*	*Nozzle Temp. °C Max.*	*Blade Temp. °C Max.*	*Nozzle and Blade Alloys **		*Nominal Blade Life-hours*
							Nozzle	*Blades*	
Ruston & Hornsby Mark TA	Base Load Generator	4·0	754	730	–	–	Nimonic 80A X40 (Post 1967)	Nimonic 90	6000 - 7000
Ruston & Hornsby Mark TF	Base Load/ Emergency Generator	6·5	760	730	–	–	Nimonic 90	Nimonic 90	Not yet realised very low usage
Allen 500 kw	Base Load Generator	9·6	820	730	–	–	Nimonic 90 (Pre 1965) X40 (Post 1965)	Nimonic 90	10,000 - 11,000
Centrax 500 kw	Base Load Generator	5·25	850	740	–	–	X40	Nimonic 90 Nimonic 105 (Post 1967)	
AEI G.6	Main Propulsion Boost	5·68	810	750	–	–	Nimonic 90	Nimonic 90	Not yet realised
R.R. Marine Proteus Max. Rating 3,500 B.H.P.	Main Propulsion	7·32	850	780 690 (At 2,000 B.H.P.)	 1st 685 2nd 565 3rd 490 4th 433	 632 519 443 412	X40	Nimonic 105	ca 2000 (Fast Patrol Boats)
R.R. Olympus TM1A Max. Rating 24,000 B.H.P.	Main Propulsion Boost	9·7	882	780 (At 17,000 B.H.P.)	1st 777 2nd 618 P.T.535	685 571 468	X40	Nimonic 105	3000 (Projected)
R.R. Tyne Max. Rating 4,250 B.H.P.	Base Load Generator and main propulsion	11·5	900 (approx. 70°C of Blade cooling)	–			C242	Nimonic 105	2000 (Projected)

* Pre 1965 blade alloys were not pack aluminised.

fuel to be carried for the same displacement and the light and compact gas generator could be removed easily for maintenance, permitting rapid engine changes and improved availability of ships.

Thus, in 1963, the policy decision was taken to employ a marinised aircraft gas turbine for boost propulsion in future new construction. This decision was extended in 1967 to the employment of engines of the same type for cruise propulsion. Subsequent development has led to the introduction of marinised versions of the Proteus, Olympus and Tyne engines with maximum ratings of 3,500 bhp, 27,200 bhp and 4,250 bhp respectively. Some of the important parameters of these engines and other turbines in the Fleet are indicated in Table 1.

Operational Factors

In general, marine gas turbines operate for much of their life at a lower fraction of their total power, and rates of power change are less onerous than in aircraft engines. Thus, whilst operating temperatures and thermal stresses may be more favourable in the marine engine, other factors may tend to impose more severe operating conditions. Ambient pressure and temperature will normally be higher and may influence cooling depending on the climatic conditions. The use of diesel fuel in place of kerosene is dictated by economic and logistic factors and results in higher flame temperatures, greater flame luminosity and a higher sulphur content in the combustion products. In addition, sea salts are ingested by the air intakes and with the fuel, since fuel tanks are normally ballasted with sea water.

Although certain specific problems have been related to the several adverse factors, the most important indication has been evidence of nozzle vane and turbine blade corrosion due to the intake of sea salts. To date, few failures have occurred in service in the Fleet due to the conservative operating temperatures which under normal running conditions are generally in the range 730 - 750°C, with only short periods at maximum rating and the associated higher temperatures. However, with the trend to higher ratings, the desire to increase time between overhauls and ultimately to achieve greater efficiency by operating at higher turbine inlet temperatures, it is anticipated that such corrosion could become the most significant factor in determining overhaul life and efficiency.

This paper sets out to review briefly the information that is available on corrosion in marine gas turbines, to indicate those problems which require solution and to consider some of the feasible approaches to its control. In addition the supporting research and development programme aimed at understanding and controlling such corrosion is outlined.

Corrosion of Nozzle Vanes and Turbine Blades in Service

The incidence of corrosion in service in the Royal Navy up to August, 1967, has been detailed elsewhere[1, 2] and subsequent experience has not materially changed the position. Apart from isolated instances of failure, the only significant rate of corrosion of nozzles or blades has occurred in Proteus gas turbines installed in the Brave Class patrol boats, where sea salt contamination is generally considered to be greater than in engines fitted in larger vessels. Knitted mesh air filters are normally fitted in air intake ducts. Isolated instances of serious corrosion in the early 1950's in MV Gatric and G2 engine installations in similar ships were considered to be associated with accidental overheating to about 925°C. When temperatures were limited to below 875°C the corrosion was not appreciable. Three separate failures of Nimonic 90 first stage nozzles in Allen 500 kilowatt turbines (maximum temperature 735°C), in larger vessels were related to heavy intake of sea water during rough weather in two instances, and salt spray and diesel engine exhaust fumes in a further instance. The exceptional nature of these failures in the Allen turbines is illustrated by the fact that two engines were run for 11,000 hours before salt corrosion had a sufficiently significant effect to necessitate reblading. No failures have been encountered since 1965, when X40 nozzles were substituted for the original Nimonic 90, in spite of the fact that the maximum turbine inlet temperature has been raised to 820°C, normal operation being rarely above 730°C. The use of X40 nozzles and pack aluminised Nimonic 105 blades in Proteus engines in the Brave Class, with a maximum inlet turbine temperature of 820°C (normal turbine inlet temperature 750°C, with 10% running at 780°C), results in an anticipated life of about 2,000 hours.

Experience of corrosion in service has been backed up by full-scale running of test engines under controlled environmental conditions by the Naval Marine Wing at the National Gas Turbine Establishment (NMW, NGTE).

The Corrosion Phenomenon

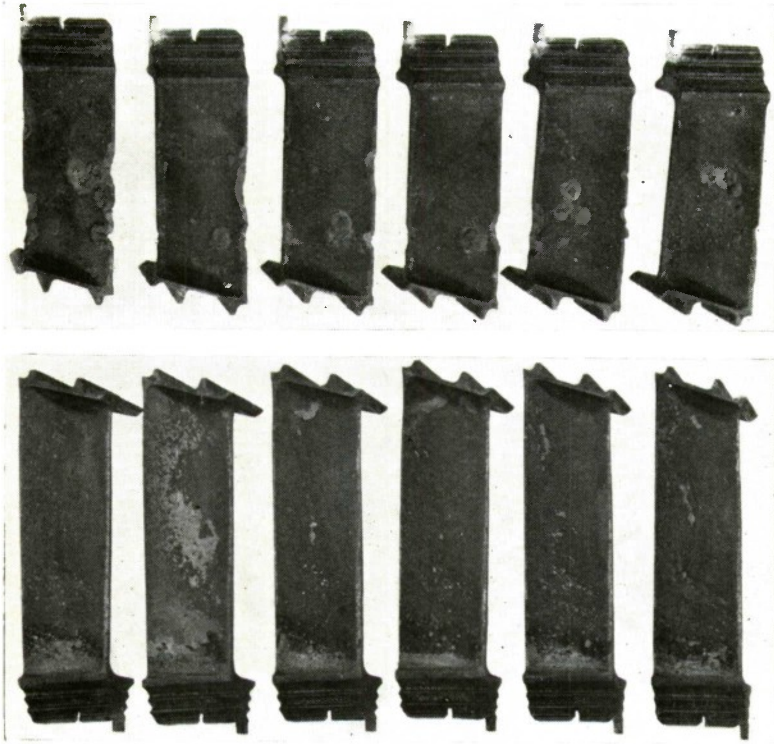
The characteristic effects of high temperature corrosion of gas turbine nozzle and blade materials have been recognised since about 1950[1, 2, 3, 4] and many examples have been documented in the literature. Superficially in severe examples the effect may appear as erosion of blade aerofoil sections with evidence of incipient fusion or blisters or deposits on surfaces. The surface of the corroded area may show considerable variation in colour from green through brown to black. Widely ranging degrees of severity of corrosion

have been observed, and in a particular engine attack may be localised and affect only nozzle guide vanes or first stage turbine blades or both. Severe attack is normally confined to the concave surfaces and the convex areas show little evidence of corrosion. Typical examples of the macroscopic appearance of corroded components are shown in Figs. 1, 2 and 3.

FIG. 1. Corroded nozzle segment from engine test at 0.5 to 1.0 ppm salt

FIG. 2. Corroded turbine blade

Metallographically, the effects of hot corrosion show certain features which are broadly independent of the detailed chemistry of the alloy or the exposure conditions and other variations in morphology which appear to be closely related to these variables. The attack is normally characterised by a deposit covering a heavy scale layer which overlays a part oxidised layer containing some sulphide. The adjacent metallic zone contains a discrete grey globular phase which is usually identified as sulphide, the globules decreasing in size with the distance from the scale layer. There may also be indications of the sulphide phase penetrating inwards along the grain boundaries of the matrix in advance of the globular zone. The part oxidised layer has been found to be substantially metallic and magnetic in certain studies on Nimonic 90 (3). Typical hot corrosion is shown in Fig. 4.



A—Pack aluminised Nimonic 105

B—Nimonic 105

Fig. 3. Corroded 1st row (A) and 2nd row (B) turbine blades from Proteus engine test after 1000 hrs. with 0.01 ppm NaC1

The deposits found on the surfaces of nozzles or blades are usually in part water soluble and the solute has almost invariably been identified as sodium sulphate, together with some calcium and magnesium sulphate, but only rarely has chloride been positively identified. The insoluble fraction of the deposit, depending on the composition of the alloy, may contain oxides of nickel, cobalt, chromium, iron, titanium, aluminium and silicon, often associated with small amounts of carbonaceous material.

The outer scale layer underlying the deposit may be largely nickel oxide (NiO) and spinels based on chromium, nickel, cobalt and iron. The nature of such spinels depends largely on the composition of the substrate alloy. In some instances, the outer scale layer may have a striated or laminar appearance which is usually assumed to relate to cyclic conditions of operation, possibly fuel rich conditions during start up (see Fig. 5). The adjacent part oxidised layer is generally found to be largely Cr_2O_3, together with base metal impoverished in chromium, with effective enrichment in the ferromagnetic alloying elements. Some investigators have identified nickel sulphide in this zone, and it has been suggested that the surface mounds or tumours may result from the formation of nickel sulphide eutectic which melts at 643°C and exudes to the surface.

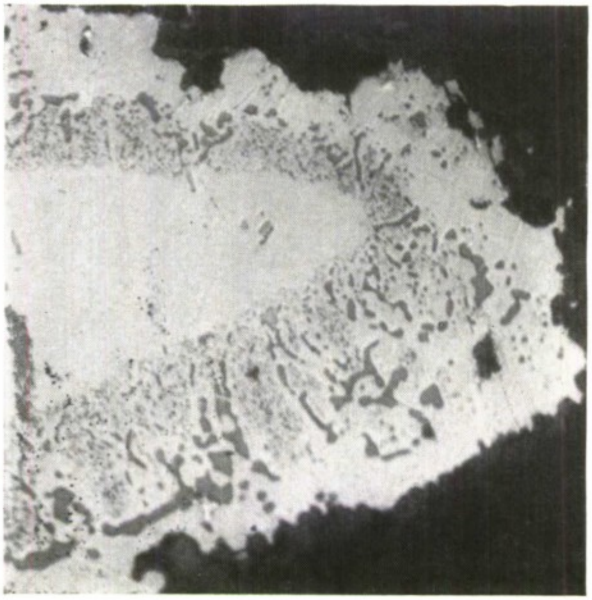
In general, in the region of attack, penetration of the base metal is uniform, but components protected by coating may show isolated pockets of corrosion, presumably associated with localised coating degradation or failure.

The corrosion effects found in marine gas turbines have sometimes been considered syonymous with a particular type of failure found on certain high nickel alloys in aircraft turbines and called "black plague"[5, 6]. In spite of the two phenomena having some features in common, there is as yet no definite evidence that they are in fact due to the same mechanism, although they may be related. The mechanism responsible for "black plague" has not been identified but it has been associated [6] with alloys of low chromium content, high temperatures (900°C and above) and long exposure times.

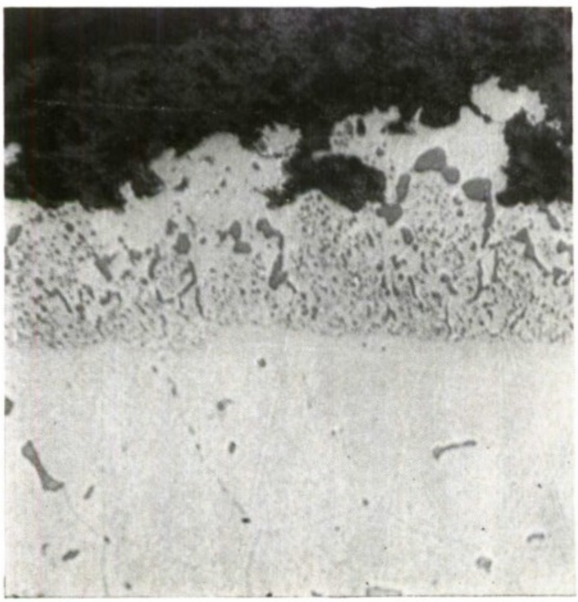
Factors Affecting Corrosion

General

In recent years the hot-salt corrosion or sulphidation phenomenon has received considerable attention and several comprehensive reviews have appeared [7, 8, 9]. Information arises from three main sources: operating experience with gas turbines in ships, test bed operation of engines under simulated marine conditions (i.e. salt injection) and laboratory investigations. Laboratory studies fall



Trailing edge x 500



Concave blade surface x 500

FIG. 4. Typical hot corrosion; pack-aluminised Nimonic 105 turbine blade from Proteus engine in land based marine location

into two main categories: comparative assessment of alloys or protective coating systems as an aid in selection or development, and fundamental researches which seek to elucidate the mechanism of attack.

The techniques adopted for testing in the laboratory include:—

(a) Crucible tests, using immersion or partial immersion in molten salts with an oxidising or inert environment over the salt. Salt mixtures are generally Na_2SO_4/NaCl with sodium chloride concentrations up to about 50%, although 25% is the most general level. Magnesium sulphate and carbon have also been employed with or without sodium sulphate [3, 5, 6].

(b) Furnace exposure tests in gaseous mixtures containing typically SO_2, sodium chloride vapour and water vapour [3]. Certain investigators have employed specimens pre-coated with sodium chloride and exposed to flowing 1% SO_2/air mixture [10].

(c) Dynamic combuster studies in which gaseous or liquid fuels are burnt and contaminants are added in the combustion air, secondary air or in the fuel. Such rig studies may be at slightly above atmospheric pressure or higher pressures approximating to turbine operating conditions, i.e. 7 - 20 atmospheres. Combusion gas velocity at the specimen test location may be in the range 100 - 1,500 ft./sec.

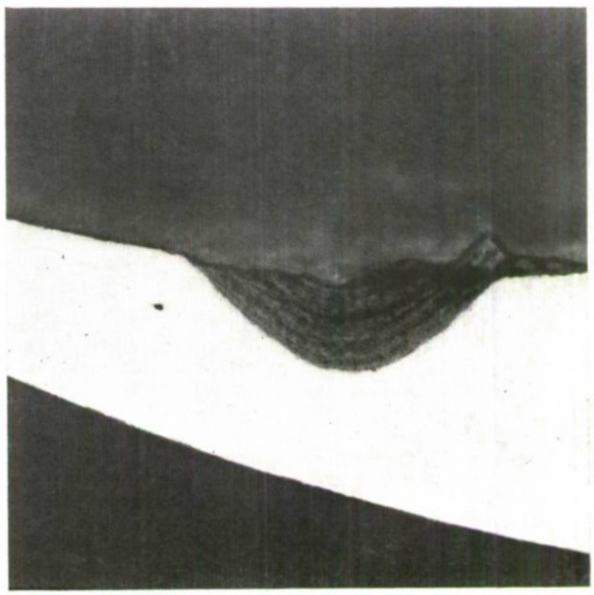


FIG. 5. Striated appearance of scale x 12

With a few notable exceptions the laboratory studies have been aimed at alloy selection or development and emphasis has been on accelerated tests which simulate actual engine corrosion and also give adequate discrimination between different materials.

In rig studies, whilst attempts have been made to achieve realistic temperature conditions, and, in a few instances, operating pressures, compara-

tively little attention has been paid to modelling the fluid dynamics and deposition mechanisms which obtain in the actual engine, and contaminant levels have generally been set higher than normally apply in the practical case. No experimental studies have been made on specimens under stress, and this factor has apparently been ignored because, in general, laboratory techniques appear to produce a sufficiently close simulation of the effects which are observed in service or in engine tests. Some attempts have been made to introduce thermal fatigue into certain studies [11] and its influence is considered to be an important element in promoting breakdown of protective films on components [12].

Environmental and Material Factors

The high temperature hot corrosion encountered in marine gas turbines is considered to become significant at temperatures above about 700 - 750°C. There are some indications that the effect may show a maximum rate at temperatures between 750 - 900°C and also an upper temperature limit, above which normal oxidation becomes the predominant process[16]. The essential features are generally considered to be the formation of a molten slag containing a high concentration of alkali sulphate on the metal surface with subsequent breakdown of the protective film on the metal, followed by interaction of the metal with the slag to produce sulphidation with accompanying accelerated oxidation.

There is considerable evidence that sodium sulphate by itself is not particularly aggressive [8] but when contaminated with other materials, particularly sodium chloride, other alkali metal salts, or carbon, significant hot corrosion occurs.

Seawater contains all the necessary constituents (see Table 2) to form an alkali sulphate slag contaminated with sodium chloride. However, the sulphur content of the fuel is usually invoked to explain the formation of the sulphate in the necessary quantity. Burning of the fuel, which may contain up to 1% sulphur, results in the formation of combustion products containing SO_2 and SO_3, which are presumed to produce sulphation of sodium chloride ingested in the air or from the fuel. Rig tests have indicated [13, 14] that reducing the sulphur level in the fuel to 0·0002% does not prevent corrosion and it seems likely that sea salt contains sufficient sulphur to sustain attack. The sodium sulphate from whatever source it may arise is generally considered as a convenient medium for concentrating the sulphur [15].

Substantially all of the existing proprietary nickel and cobalt base super alloys and many experimental materials have been tested for resistance to salt accelerated hot corrosion in the extensive investigations which have been made. In general, the resistance of materials depends to some extent on the method of testing and assessment, and the relative merit of alloys may change with temperature. From these investigations it appears clear that chromium content may be the most important single factor in determining resistance to hot corrosion and at least 15% is considered essential. In general, the higher the temperature the greater must be the chromium content for resistance. Other elements may have a beneficial influence but the extent of any improvement is less marked at high chromium levels [16, 17, 18, 19]. Titanium and aluminium are considered beneficial in nickel base alloys but there are indications that they must be present together, and in the correct ratio. Separately in high percentages they may be detrimental[16, 17]. Cobalt in nickel base alloys may also produce enhanced resistance but tungsten may be beneficial up to 950°C and harmful at higher temperatures [17]. Iron at the 10 - 20% level appears innocuous in nickel base alloys with up to 20% chromium at temperatures up to 950°C but may be detrimental at higher temperatures [17]. The influence of molybdenum is generally considered harmful but the effect appears to be related to the particular chemistry of the alloy and is most detrimental in complex compositions. Silicon is also considered harmful [19].

TABLE 2. Composition of Sea Water

Element or Radical	*Concentration ppm*
Cl	18,980
SO_4	2,650
Bicarbonate	140
Br	65
F	1·25
Boric Acid	26
Na	10,560
Mg	1·25
Cu	400
K	380
Sr	13

There are some indications [16] that the best cobalt base alloys may show better resistance to salt corrosion than the best nickel base alloys at high temperatures of around 1050°C, but up to 950°C there appears little to choose between the two types. The nominal compositions of a selection of typical nickel and cobalt base alloys are

TABLE 3. Nominal Compositions of Typical Nickel and Cobalt Base Gas Turbine Alloys

Material	Nominal Chemical Composition %															
	C	*Si*	*Fe*	*Mn*	*Cr*	*Ti*	*Al*	*Nb*	*Ta*	*Co*	*Mo*	*Ni*	*Zr*	*B*	*W*	*V*
Nimonic 81 (M313)	0·06 max	0·4 max	2·0 max	0·5 max	28/32	1·5/2·0	0·7/1·1	–	–	2·0 max	–	Bal	0·01/0·1	0·001/0·01	–	–
IN-718	0·1	0·75	17	0·5	20	0·6	0·5	5·0	–	–	3·0	Bal	–	–	–	–
Nimonic 90	0·13	1·5	5·0	1·0	18/21	1·8/3·0	0·8/2·0	–	–	15/21	–	Bal	–	–	–	–
C 242	0·3	–	1·0	–	20	0·3	0·2	–	–	10	10	Bal	–	–	–	–
Nimonic 105	0·2	1·0	1·0	1·0	13·5/16·0	0·9/1·5	4·2/4·8	–	–	18/22	4·5/5·5	Bal	–	–	–	–
Nimonic 115	0·15	–	–	–	15	4·0	5·0	–	–	15	3·5	Bal	–	–	–	–
IN-738-X	0·17	–	–	–	16	3·4	3·4	0·9	1·75	8·5	1·75	Bal	0·1	0·01	2·6	–
MAR-M421	0·15	0·2 max	1·0 max	0·2 max	15·8	1·8	4·3	2·0	–	9·5	2·0	Bal	0·05	0·015	3·8	–
Udimet 700	0·07	–	–	–	15	3·2	4·3	–	–	17	5·3	Bal	0·04	0·02	–	–
IN-713C	0·12	–	–	–	12·5	0·8	6·1	2·2	–	–	4·2	Bal	0·10	0·012	–	–
IN-100	0·18	–	–	–	10	5·2	5·6	–	–	15	3·0	Bal	0·09	0·015	–	0·65
MAR-M246	0·15	–	–	–	9	1·5	5·5	–	1·5	10	2·5	Bal	0·05	0·015	10	–
M21	0·13	–	–	–	5·7	–	6·0	1·5	–	–	2·0	Bal	0·12	0·02	11	–
X40	0·5	–	–	–	25	–	–	–	–	Bal	–	10	–	–	7·5	–
WI 52	0·45	0·25	2·0	0·25	21	–	–	2·0	–	Bal	–	1·0	–	–	11	–
MAR M302	0·85	–	–	–	21·5	–	–	–	9·0	Bal	–	–	0·20	0·005	10	–
MAR M322	1·0	–	–	–	22	0·8	–	–	4·4	Bal	–	–	2·3	–	8·8	–
MAR M509	0·60	–	–	–	23·5	0·2	–	–	3·5	Bal	–	10	0·5	–	7	–

given in Table 3. It is significant that the present proprietary cobalt base alloys generally have a higher chromium level (20 - 25%) than the corresponding nickel base materials in which increase in chromium level degrades the properties. The existing nickel base superalloys were developed primarily to provide high creep and stress-rupture strength, combined with oxidation resistance. Attempts are now being made to develop alloys of comparable strength and structural stability, but with higher (20 - 30%) chromium content. One such alloy is Nimonic 81 (see Table 3) which has 30% chromium and creep properties between those of Nimonic 80 and Nimonic 90.

In the cobalt base alloys, nickel appears detrimental[16], tungsten and niobium harmful at 1038°C and titanium slightly deleterious. Aluminium may be beneficial[20].

The influence of minor elements on nickel and cobalt base alloys has been studied recently[17, 20]. Boron, zirconium and niobium appear detrimental in nickel base alloys, yttrium innocuous, rhenium and lanthanum may be beneficial and cerium is believed to be very effective in enhancing corrosion resistance. The straightforward oxidation behaviour of the nickel base alloy Inconel 718 modified by increasing the silicon and manganese and adding 0·25% samarium has been studied[21] and shows an improvement over normal Inconel 718.

In cobalt base alloys niobium may be harmless at 950°C but detrimental at 1050°C. Hafnium appears innocuous[16] and zirconium may be beneficial up to 950°C and innocuous at higher temperatures[17]. Yttrium, lanthanum and cerium[16] are apparently slightly beneficial[17]. There are some indications that in cobalt base alloys with 18% chromium, 7·5% tungsten, 8·2% iron, 7·1% nickel and 5·6% aluminium, reduction in manganese and carbon[20] may improve corrosion resistance.

In general, there are few data on the influence of carbon content in either nickel or cobalt base alloys. High carbon (about 0·85%) may be detrimental in cobalt alloys[16], and it has been observed[20] that the hot corrosion resistance of a nickel base alloy decreased as the $M_{23}C_6$ (mainly $Cr_{23}C_6$) content increased during exposure at temperature. This effect may be related to the reduction in the effective chromium level.

Corrosion Mechanism

The precise mechanism of hot corrosion remains obscure and although certain of the part processes have been identified, the detailed chemistry of the process has not yet been elucidated.

It is not clear whether chloride ion plays a significant part since HCl or volatile chlorides may be formed, which are lost and hence not detected in corrosion deposits. This may be a factor in promoting the breakdown of oxide films by reduction and volatilisation. Sodium chloride may act purely as a source of sodium for combination with sulphur to form sodium sulphate or as a means for lowering the melting point of sodium sulphate, the Na_2SO_4/NaCl eutectic melting at 621°C. Thus, if a molten slag is required for corrosion to be aggressive then the influence of sodium chloride could be to depress the lower limit of temperature for accelerated attack. Lithium, which also forms low melting point eutectics, also accelerates corrosion, but magnesium and calcium should not form molten sulphates and are reported to be innocuous[14], although magnesium sulphate/carbon mixtures have been found to produce corrosion[5].

The incubation period before sulphidation commences has been shown to increase with the oxide film thickness[22, 5]. Exposure of NiO and Cr_2O_3 to molten Na_2SO_4/NaCl mixtures demonstrated that reaction occurred only in the presence of carbon[22] and it is known [8] that Na_2SO_4 and SO_2 are oxidising to most high temperature alloys when reducing agents are absent. Thus, destruction of the oxide protective films by molten slag deposits through a solution or reaction mechanism may only be possible in the presence of free carbon or under reducing conditions. The striated nature of scales found on certain corroded components indicates cyclic environmental conditions which at times may be locally reducing, and it is known that "sooting" can occur under certain combustion conditions in the gas turbine.

The absence of deposits on specimens tested at 1093°C may indicate that the vaporisation point of the slag has been reached[7] and this could account for oxidation becoming the predominant process at high temperature.

Extensive breakdown of the protective layer is not a necessary prerequisite for sulphidation, since sulphur compounds may gain access through cracks or defective areas in the scale. In addition, sulphur may diffuse through the oxide layer. Sulphur gaining access to the metal will form chromium sulphides preferentially, since these are believed to be more stable than most metal sulphides, with the exception of those of manganese, the rare earths and the actinides[9, 17]. Cr_2S_3 has been identified, and although the oxidation resistance of Cr_2S_3[17] is not established it is assumed that chromium rich sulphides are oxidised and that the sulphur which is liberated diffuses into the alloy and forms further chromium sulphide. The improverishment of the matrix in chromium, particular adjacent to chromium sulphide particles, renders it readily susceptible to oxidation. Thus,

the sequence of sulphidation followed by oxidation can proceed progressively deeper into the alloy matrix and can be self-sustaining once started, since it may be independent of an external source of sulphur. The influence of cerium additions is consistent with this mechanism since cerium probably forms a more stable sulphide than chromium. Alternative explanations of the effect of cerium are suggested later. The apparently better corrosion resistance of cobalt base alloys under certain conditions may be related not only to chromium content but also to a lower solubility of sulphur or a much lower diffusion constant[17].

The identification of NiS and Ni_2S_3 in certain corroded specimens[5, 18] has led to the suggestion that following chromium impoverishment by sulphidation then the nickel/nickel sulphide eutectic may form (melting point 643°C). This may result in accelerated oxidation of metal dissolved in the eutectic due to higher activity in the absence of protective surface oxide films on the liquid. Evidence of liquid phases is based mainly on data from crucible tests in instances where severe corrosion occurred[3]. Liquidus determinations on corrosion deposits from actual engine components[10] have indicated data incompatible with any temperature achieved in operation but such evidence in inconclusive, since compositional changes may have occurred during cooling.

Practical and Theoretical Considerations

The Dieso fuel oil employed in gas turbines in the Royal Navy conforms to Specification DEF.2402B and a sulphur content of 1·0% maximum is specified. In practice the average sulphur level is about 0·45%. Sea water in the fuel may result in up to 10 ppm salt content (expressed as Na). After settling and by employing coalescence filters in the fuel lines, it is possible to limit the salt contamination to a maximum of 0·6 ppm and an average level of 0·3 ppm[23].

Measurements of sea salt contamination of the marine atmosphere have been made by the Royal Navy in conjunction with NGTE and by the USN[24, 25]. Apart from abnormal weather conditions giving rise to fog or haze, which may produce large increases in the salt burden of the atmosphere, contamination levels (expressed as NaCl) found outside engine intakes have been estimated[24] as follows for frigates and larger ships:—

(1) Fair weather—0·01 - 0·05 ppm; particle size five microns or less.

(2) Moderate weather—up to 0·1 or 0·2 ppm; some particles may be up to about 20 microns.

(3) Rough weather—up to 1 ppm in gale conditions, higher in severe gales; some very large particles.

For vessels such as fast patrol boats the data[24] are very dependent upon ships' speed, weather, proximity of other ships and other factors, and salt levels at engine intake vary from 0·01 ppm to several ppm.

Work on particle size analysis[25] has indicated that the larger droplets contribute a greater proportion of the salt burden as the seas become rougher. The aerosol concentration is generally considered to include those particles smaller than 4 to 5 microns[25] and this does not increase as rapidly as the more massive particles as the wind speed rises.

The use of knitted mesh air filters in the air intake ducts has demonstrated that the salt burden can be reduced to 0·01 ppm if the filtration is correct. In general[23] the greatest efficiency of separation by filtration is found when the relative humidity is high and falls off with decreasing humidity. At low humidity, filtration may be only about 10% efficient.

The fuel/air rates[23] for the Proteus and Olympus TM1A engines at current service maximum ratings are shown in Table 4 below.

TABLE 4. Fuel/Air Rates for Proteus and Olympus TM1A engines.

Engine Types	*Power BHP*	*Fuel Rate (lbs/hp/hr)*	*Air Mass Flow (lbs/sec)*
Proteus	3,500	0·645	41·6
Olympus TM1A	24,000	0·505	230

Simple calculation indicates that under these conditions, and assuming concentrations of salt in fuel of 0·3 ppm (Na), i.e., 0·76 ppm NaCl, and in air of 0·01 ppm (NaCl) approximately equal quantities of salt will be ingested via the fuel and the air, as shown in Table 5 below.

TABLE 5. Salt Ingestion Rates.

Engine Types	*Total Salt as NaCl(lbs/hr)*	
	Fuel	*Air*
Proteus	$1{\cdot}72 \times 10^{-3}$	$1{\cdot}49 \times 10^{-3}$
Olympus TM1A	$9{\cdot}11 \times 10^{-3}$	$8{\cdot}28 \times 10^{-3}$

Turbine entry temperatures for various conditions have been given in Table 1, together with estimated nozzle and blade temperatures for certain conditions of operation of the Proteus and Olympus engines.

In the literature, attention has been devoted to the vapour pressures of NaCl and Na_2SO_4 and the thermodynamics of formation of Na_2SO_4 from NaCl, H_2O, SO_2 and SO_3 in the high temperature environment of the gas generator(26). The vapour pressures of various credible concentrations of the solid contaminants from the fuel and air at turbine operating pressures have been discussed in relation to dew points or frost points and the formation of deposits(1, 2, 6, 27). It has been demonstrated(26) that corrosion does not occur in the absence of condensation, the sulphur potential of gaseous mixtures of air/SO_2 and air Na_2SO_4 being insufficient to form sulphides of the normal super alloys. However, the theoretical predictions have not always been borne out in practice and corrosion has occurred at temperatures above the anticipated dewpoints of the particular contaminant concentrations employed in certain rig experiments. This has been explained on the basis of imprecise vapour pressure data, temperature gradients, local variations in contaminant concentration, or lowering of vapour pressure by the presence of other compounds. No determinations of vapour pressure appear to have been made under the complex conditions which are believed to exist in the gas turbine environment. It must be assumed that the effect of increased pressure will be to make the conditions more corrosive.

Based on calculation(26) from available thermodynamic data, it has been assumed that conversion of NaCl to Na_2SO_4 will be complete at the temperatures and pressures of the gas turbine. This theoretical prediction is supported, although not completely, by studies of the behaviour of sodium salts in flames(28). However, the thermodynamic calculations and flame studies do not take into account the kinetics of the reactions and it must be noted that residence times in the gas turbine are only of the order of milliseconds compared with possibly seconds in other combustion systems such as boilers. Thus, it may be incorrect to assume complete conversion of NaCl to Na_2SO_4. A further factor is that salt may reach the turbine by four routes, including the fuel, the primary air, secondary air and nozzle or blade cooling air. Thus, not all of the salts will have been exposed to flame temperatures. In addition, only part of the salt present in the intake air after the filters will reach the turbine, since some may be removed in the compressor, etc.

Some early studies (4, 22), indicated the importance of electro-chemical effects, and a recent thermodynamic study of corrosion in fused sodium sulphate (29) has thrown new light on the electrochemistry of the molten salt/metal system. This basic approach leads to diagrams similar to those of Pourbaix for aqueous systems and if applied, could lead to a better understanding of the mechanism of corrosion in the gas turbine.

Control of Corrosion

General

Measures taken at present to control corrosion in the marine gas turbine involve filtration of inlet air and fuel to reduce salt contamination, limitation of operating temperatures and the use of protective coatings on alloys which have the required mechanical properties together with a reasonable level of corrosion resistance. However, if the full potential of the gas turbine in marine propulsion is to be exploited, then alternative or additional methods must be evolved which are less restrictive in operating parameters and give improved availability.

The potential options include reduction of salt contamination of fuel and air, use of fuels of lower sulphur content, the use of fuel additives, and the development of improved alloys and/or coatings. A further possibility which has been suggested is to raise the operating temperature on the basis of indications that corrosion may be reduced at the higher temperatures. This argument can be dismissed since it might only result in corrosion occurring in a later and cooler portion of the engine and would be no solution.

Air

Efforts are being made to improve the efficiency of intake filters without producing an unacceptable pressure drop. Clearly, filtration can never be 100% efficient within the range of required mass flow and acceptable pressure drop. At best only a reduction in contamination level can be expected, but this may be significant taken in conjunction with other measures.

Fuel

Further efforts are being made to limit the level of sea water contamination of the fuel and to improve efficiency of filtration. However, in view of the apparent solubility of salt in fuel (about 0·1 ppm(12)) and the possibility that organic substances may be present or that salts may be absorbed on organic substances present in the fuel or the sea water, there is probably a lower limit which cannot be improved upon.

Reduction of the sulphur content of fuel does not appear to be effective (13) and might also impose operational and logistic problems apart from possible economic penalties.

The use of fuel additives is an approach which appears attractive but might not provide unqualified benefits. The objectives would be to employ additions resulting in passivation of metal surfaces or in solid or completely gaseous contaminant products following combustion, by modifying the solidus temperatures or vapour pressures of the potential slag forming reagents. Such additions would need to be soluble or miscible with the fuel and capable of ready mixing. However, this approach might entail logistic problems and could also impair engine efficiency due to fouling by solid materials. In spite of these disadvantages, active consideration is being given to the selection of suitable additives for appraisal.

Alloys

Although the use of coatings may result in a reduction in corrosion and an extended life for candidate nozzle and blade materials, they must be considered only as a palliative measure, since it seems unlikely that an indefinite life can be obtained due to coating imperfections or local degradation and breakdown. Thus, the most effective long term solution lies in the provision of improved alloys which have a high inherent resistance to corrosion in the environment of the marine gas turbine.

Development is proceeding on the production of improved nickel and cobalt base alloys. The most obvious approach is to evolve alloys of higher chromium content and the influence of aluminium content should be investigated further. In view of the apparently beneficial effect of cerium, additions of other strong sulphide-forming elements must be investigated. In this respect, the influence of manganese content should be explored and also the influence of strong carbide formers such as hafnium which could prevent the formation of $Cr_{23}C_6$.

It should also be noted that the influence of cerium may be more subtle than simply acting as a getter for sulphur. Cerium additions have been employed for many years in nickel-chromium alloys as a means of improving the life of electric resistance elements by modifying the oxidation behaviour. Thus, the effect may be partly attributable to an improvement in the protective properties and durability of the oxide film. In general, the metals which have greatest oxidation resistance are those having the closest packing of both the anionic and cationic lattices (*e.g.* nickel, and chromium are among the smallest of the 2+ and 3+ ions). This results in the lowest rates of diffusion for both the anionic and cationic species. The influence of gettering elements, such as cerium, may be to tie up impurity elements which would otherwise be incorporated in the oxide film and could result in additional vacant sites in the lattice and enhance diffusion. The fact that sulphur may diffuse through Cr_2O_3 has been demonstrated[17] and elimination of impurity ions from the Cr_2O_3 lattice may help to reduce the rate. The protective properties of the oxide film will be dependent on its ability to accommodate strain and to self-heal by sintering. Impurity atoms in the film may tend to reduce the plasticity and hence gettering elements may help in preserving purity and ductility, in addition to eliminating vacant sites.

Clearly close attention should be devoted to the crystal chemistry of protective films since this may be a fruitful avenue to alloys of improved corrosion resistance.

Coatings

Aluminised coatings to enhance the high temperature corrosion resistance of the exhaust manifolds of the internal combustion engines of military aircraft were introduced more than 25 years ago. It is therefore not surprising that similar coatings have found application in the gas turbine.

In the gas turbine engine protective coatings must have a number of properties including:—

Resistance to high temperature corrosion or erosion by flames and hot combustion products; resistance to impact damage;

resistance to mechanical and thermal fatigue and thermal shock [30].

In addition, the coating must have long term stability against diffusion, must not impair the properties of the substrate alloy, have a high melting point, a coefficient of thermal expansion close to that of the substrate and adequate ductility to withstand thermal fatigue and to accommodate creep of the substrate. Ideally, it should also be self-healing in the event of cracking or other local breakdown. Not surprisingly few coatings possessing the majority of these properties have yet been evolved.

Glass based ceramic coatings were employed [5] initially to protect nickel base alloys against hot salt corrosion but were replaced by aluminised coatings which had better stability and did not suffer from temperature limitation. Aluminised coatings applied to nickel base alloys by pack cementation have been studied extensively in recent years and the structure and degradation mechanism of such coatings depends on NiAl, nickel-aluminide, modified by other elements from the substrate alloy. The coating process is normally adjusted to produce a coating which is predominantly beta NiAl. Degradation is due to selective removal of aluminium by oxidation and subsequent spalling of Al_2O_3[31]. The properties

and adhesion of the coating formed on a particular alloy are dependent on the composition of the substrate[12, 32]. The thickness of aluminide coatings is normally in the range 0·001 - 0·005 in. Similar coatings have been found effective on cobalt base alloys such as X40, but less so than with the nickel base materials.

Extensive development of coatings has taken place over the past few years [33-40] and a wide variety of types have evolved. Many are modifications of the NiAl or CoAl types and include Al-Cr[34, 35, 36], Al-Fe, Al-Si[35], TaAl or Ta + CoAl [37], Al-Cr-Si[35], berryllides (e.g., Nb_2Be_{17} and Ta_2Be_{17}) [35]. Recently coatings of ZrO_2 have been described [38] and claimed to limit temperatures on nickel base blading, but the corrosion resistance of such coatings has not been investigated. Tantalum diffusion coatings are reputed[34] to be particularly effective if used as a precoating for Cr-Al coatings; it is claimed that tantalum, which has a large atomic radius, functions as a diffusion barrier to chromium and aluminium.

It is generally accepted that in the event of local coating failure the further corrosion resistance will be that of the substrate alloy. Normally the life of coatings in engine service is considered to be no greater than a few thousand hours.

Basic Research

In order to arrive at the most effective answer to hot salt corrosion, the basic mechanism must be established. Unfortunately research to date has not provided the complete explanation, although there is a better understanding of certain of the part processes. It is now clear that a quick answer will not be found but in the long term knowledge of the mechanism may enable scientific principles to be applied to alloy development and possibly result in economy of effort, as compared with the ad hoc approach.

The corrosion phenomenon is complex and must be broken down into its part processes. Initially, it is desirable to establish the chemistry of the reactions taking place between combustion products and contaminants during short residence times. A clearer picture of the solid, liquid and vapour species present in the environment should help to clarify the deposition processes which lead to the formation of slags. Preferential corrosion of the concave surfaces of blades or nozzles are indicative of the importance of the deposition process and the fluid dynamics of the system are clearly of interest. A knowledge of the species present in the gas phase and the deposition processes should help to clarify the mechanism of interaction of the environment with the metallic components.

Research and Development Programme

The current research and development programme of the Royal Navy in the area of hot salt corrosion is broadly based and collaborative arrangements exist with the U.S. Navy Programme.

The present U.K. Programme includes both ad hoc work to provide early results and longer term more fundamental investigations. A combuster rig, operating on dieso fuel has been installed at the Admiralty Materials Laboratory, and has recently been commissioned (see Fig. 6). The rig operates at slight positive pressure and is designed to test simultaneously 15 simulated aerofoil-section test specimens (see Figs. 7, 8 and 9). Sea water can be injected with the fuel or with the combustion air or into the combustion projects. Velocities up to about 1500ft./sec. at the test section are obtainable. This equipment is designed to test alloys or coatings at realistic temperatures and is intended to function as a sorting test to aid materials selection. Existing and new proprietary alloys and coatings are being assessed. The test conditions have been adjusted to reproduce the type of corrosion which has been encountered in service and in engine tests on well established alloys. The investigation is being supported by a wide range of characterisation techniques such as scanning electron microscopy, electron probe micro-analysis, X-ray diffraction and conventional metallography. In addition it is the intention to develop methods for determining the species present in the hot gas environment.

Proprietary coatings are being developed on both an *ad hoc* and a fundamental basis and promising formulations will be tested for comparison with well-tried pack aluminised coatings. The influence of pre-treatment of coatings by controlled oxidation will be evaluated.

Alloy development embraces new proprietary compositions and more fundamental studies which it is hoped will lead to improved materials and better understanding of their formulation. In addition to the study of conventional metallic materials active consideration is being given to the possible use of silicon nitride ceramic components in the gas turbine. Certain possible applications including nozzle vanes are being investigated and the resistance of the material to corrosion is being assessed.

The rig programme is supported by engine testing at NGTE, Naval Marine Wing, of alloys or coatings selected on the basis of the rig tests. The engine tests are carried out initially in a Centrax engine and ultimately in a Proteus gas turbine at salt contamination levels in the range 0·01 to 1 ppm in the intake air. Previous engine tests have been made to assess the influence of salt in the air and salt in fuel.

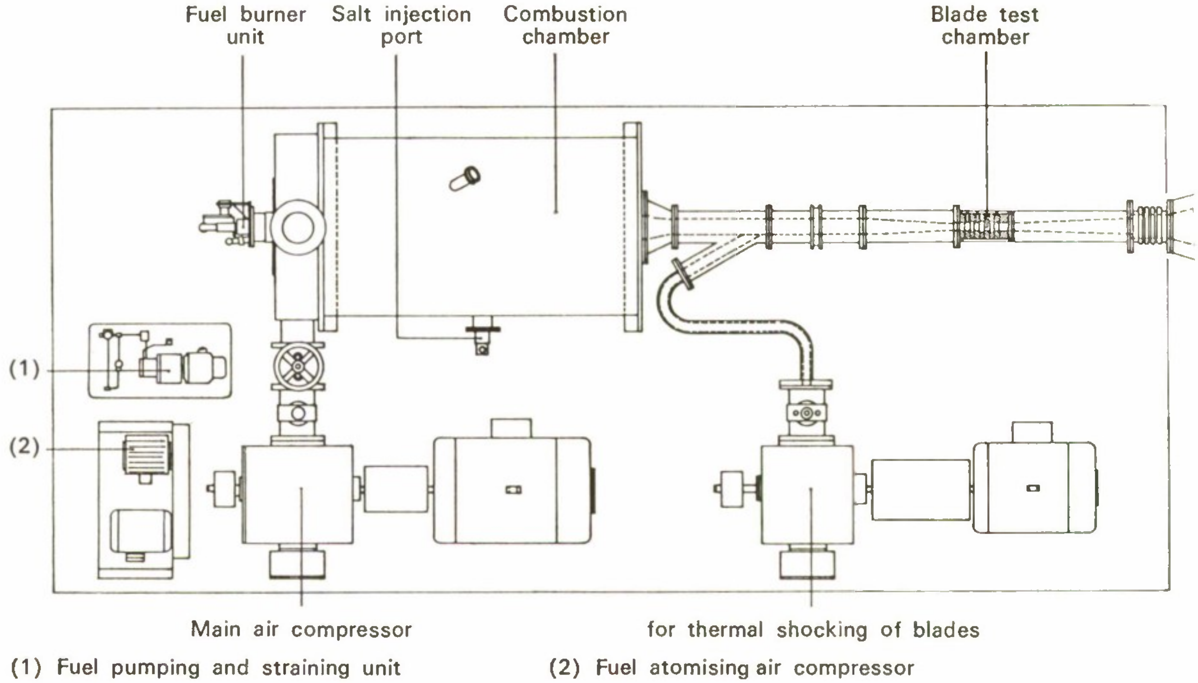
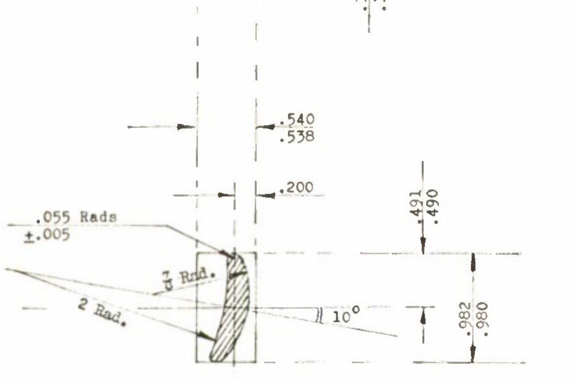


FIG. 6. A.M.L. corrosion test rig

Fundamental studies include extra mural work to elucidate the chemical reactions taking place during short residence in the combustion environment and to examine the fluid dynamics of the deposition process. A further high pressure rig is being designed for installation at A.M.L. to study the mechanism of corrosion under conditions which it is planned will simulate those obtaining in the marine gas turbine.

In addition to research and development work on alloys and coatings, effort is being devoted to further development of intake air filters and filtration techniques for fuel in order to reduce contaminant concentrations to levels acceptable for extended service.



(Dimensions in inches)

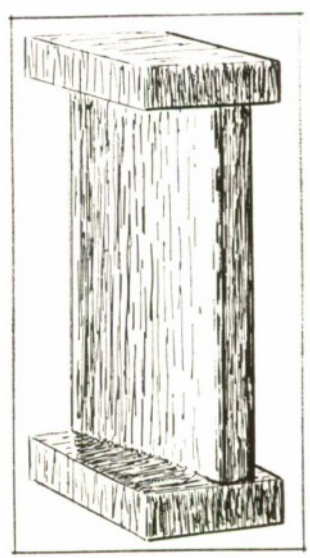


FIG. 7. Test specimen

Scale: ¼ (approx.)

Gas flow

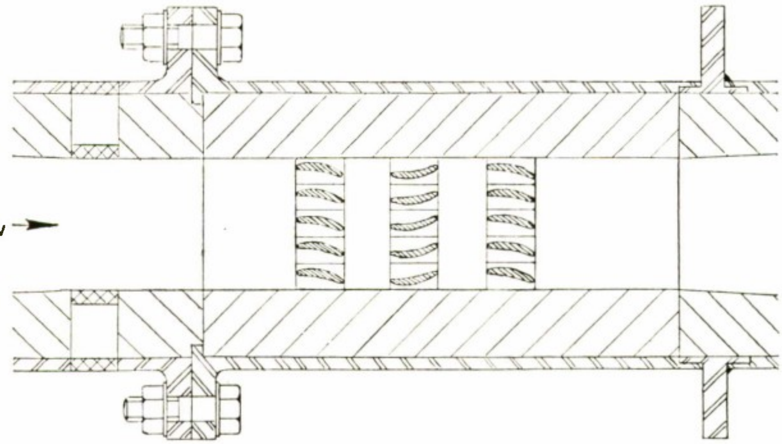


FIG. 8. Plan view of test chamber

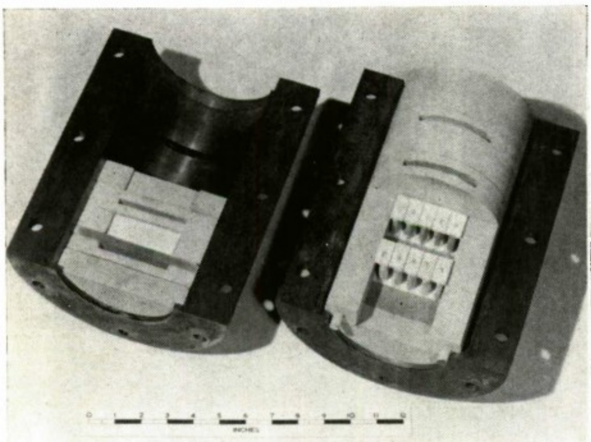


FIG. 9. Specimens and test chamber

Summary

The primary objective of the present programme of research and development is to evolve effective methods for control of salt accelerated corrosion to enable the time between overhauls and turbine inlet temperatures to be increased safely and progressively. In the short term this work will provide support for the marine gas turbines already in service and in the longer term will, it is hoped, enable the full potential of the marine gas turbine to be realised reliably and efficiently in new vessels coming into commission during the next few years.

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THE PILL-BOX TECHNIQUE FOR AIR CONDUCTIVITY MEASUREMENT

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Abstract

A novel technique is described for the measurement of the conductivity of air contained between the plates of a parallel condenser, called the Pill-Box, which is charged by a 10 MeV electron beam being absorbed in one of the plates after passing through the other one and ionising the air. Measurement is made of the condenser equilibrium voltage at which the conduction current in the air is just balanced by the charging beam. Experimental measurements are presented over a range of pressure from 1 torr to 2·9 atmospheres and in the region over which the theory is shown to be valid reasonable agreement with more conventional methods is found to exist. The attachment frequency of electrons in air at atmospheric pressure was found to be $3{\cdot}14 \times 10^7$ sec^{-1}

Introduction

The impetus of the present work came from the need to improve our understanding of the electromagnetic pulse phenomena accompanying a nuclear explosion in the atmosphere. When a nuclear weapon is exploded in the atmosphere the gamma rays emitted from it knock electrons out of the atoms in the air by the Compton effect. These electrons move away from the centre of the burst so forming a shell of negative charge. An electric field thus exists across air which has been ionized by the passage of the radiation. Therefore, a current system is set up and it is this which produces the emission of the so-called " radioflash " signal. The amplitude and duration of this signal will depend on the conductivity of the air. To calculate this involves knowing the attachment and recombination rates of electrons and ions in the air and also their mobilities. In 1963, C. L. Longmire, of Los Alamos (private communication), suggested that a way of studying these phenomena and improving our understanding of them would be to construct a device to simulate these effects in a slice of air, and he called this the " Pill-Box ". Longmire pointed out that if two metal plates, held parallel to each other, are set up with their surfaces normal to the direction of the gamma rays from a nuclear weapon, then Compton electrons knocked out of the first metal plate by the gamma ray beam would strike the second one and this Compton electron flux would be the same as if the first metal plate was not present, because the ratio of Compton flux to gamma ray flux is nearly independent of the material. The reason for this is that the range of Compton electrons in any material is inversely proportional to the number of electrons per cm^3 in it, whereas the Compton flux itself is proportional directly to the number of electrons per cm^3. If the second plate is thick enough to absorb an appreciable fraction of the gamma rays which strike it, and if the two plates are short circuited, then the current flowing from one to the other is essentially a measurement of the Compton current absorbed in the second plate and hence of the gamma ray flux. If, on the other hand, there is an open circuit condition between the two plates,

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the voltage set up across them, together with the previous measurement of the Compton current, will give the electrical conductivity of the air. An experiment of this kind was performed at Los Alamos (R. Partridge, 1964, private communication). A long duration gamma ray pulse from a nuclear explosion was produced by absorbing the neutrons from it in indium and allowing the resulting capture gamma rays to fall on the Pill-Box. It was at first thought that similar work could be done in the laboratory by using a gamma ray beam from an accelerator. However, simple calculations soon show that the intensities available from any ordinary accelerator are far too small to make the effect work. However, if an electron beam from a linear accelerator is used directly the whole situation changes and the experiment becomes feasible. The emphasis then becomes one of determining fundamental physical constants such as the attachment and recombination rates of the electrons and ions and also their mobilities. The principle is the simple one that if we have a parallel plate condenser with one plate thin enough to allow the electron beam which is travelling normal to the plane of the plates to pass through it, and the other plate thick enough to stop this electron beam, and further if the space between the plates is filled with gas, then the electron beam passing through the first plate and stopping in the second, charges up the second one and provides the electric field between the two plates. A current will flow in the gas which has been ionized by the passage of the beam. If the time constants involved are suitable a condition is reached in which the incoming electron beam current is just balanced by the conduction current in the gas and the external circuit and an equilibrium is set up. Two successive measurements under identical conditions approximating to the previously mentioned ideal cases of short-circuit and open-circuit can be combined to give a quantity which involves fundamental constants of the ionized gas. In air at pressures near atmospheric, the electron population in the gas at the end of the ionizing pulse will disappear very rapidly and the gas will then consist of ions only. By studying the way in which the voltage across the plates decays with time from the end of the pulse, constants appropriate to the ions only can be determined, and it should be possible to separate the effects of ions and electrons.

This paper describes work done using the Pill-Box method for the measurement of the various parameters involved in the conductivity of ionized air. It is presented as a novel method and at this stage reasonable agreement with previous workers' results, obtained by conventional means, is considered to be its justification. In what follows the theory of the Pill-Box is developed, the effects of sheaths and diffusion are shown to be negligible in the range of air pressure over which the theory is demonstrated to be valid and the contributions of the electrons and ions to the conductivity are considered. The apparatus and experimental procedure is described. In the experimental programme the effects of such factors as air pressure, plate separation, current density and distribution, pulse rate and humidity are examined. Experiments to measure the electron beam energy and profile inside the Pill-Box are also described. The results of all these are presented and discussed.

THEORY OF THE PILL-BOX

Charging of the Pill-Box

Consider Pill-Box with plate separation d, and external resistance R connected across the plates, and let it be irradiated normal to the plane of the plates by an electron beam in the form of a rectangular pulse of duration τ and current I with current density J (r) where r is the distance measured in the plane of plates from the axis of symmetry of the beam. If the diameters of the Pill-Box plates are much greater than their separation, then the electric field between them, E, will not vary with r, and $E=V/d$ where V is the voltage across the gap.

If σ (r,t) is the electrical conductivity of the air at r and time t from the start of the pulse due to ionization by the beam, then by the conservation of charge

$$\frac{dq}{dt} = \int_0^\infty 2\pi r \left\{ J(r) - E\sigma(r,t) \right\} dr - \frac{V}{R} \qquad \ldots (1)$$

where q is the negative charge on the central plate. Note that the resistance of the gas, R_g, is given by

$$\frac{1}{R_g} = \int_0^\infty \frac{2\pi r\sigma(r,t)}{d}\, dr \text{ and } I = \int_0^\infty 2\pi r J(r)\, dr$$

If the current density profile is given by a Gaussian, $J(r)=J(o)\exp(-r^2/L^2)$ where J(o) is the current density at r=o and L is the characteristic dimension of the beam, then $I=\pi L^2 J(o)$.

Now if the Pill-Box time constant $R_g RC/R_g+h$ where C is the Pill-Box capacitance, is sufficiently less than τ a near equilibrium will be reached before the end of the pulse and the conduction current flowing from the central plate through the gas and external circuitry will balance

the current n the electron beam. Equation (1) then becomes

$$\int_0^\infty 2\pi r\sigma(r)dr = d\left(\frac{I}{V} - \frac{1}{R}\right) \qquad \ldots (2)$$

where $\sigma(r)$ is now a function of r only.

Reaction rates

We now consider what species are present in the ionised air and how their number density depends on the ionisation and various removal rates.

Electrons and positive ions are produced by the ionisation process at the same rate but are removed at different rates by a large number of different processes. These can be classified as

(a) The attachment of electrons to neutral oxygen molecules to form negative molecular and atomic ions,

(b) The recombination of electrons and positive ions, both atomic and molecular and

(c) The recombination of positive and negative ions, both atomic and molecular.

Let those groups of processes have rate coefficients β, α_e and α_i respectively and let the number densities of electrons, positive and negative ions at a time t from the start of the electron pulse and at r be n(r,t), $N_+(r,t)$ and $N_-(r,t)$ respectively. If p(r) is the rate at which ion pairs are created by the beam per unit volume per unit time at r then we have

$$\frac{dn(r,t)}{dt} = p(r) - \beta n(r,t) - \alpha_e n(r,t)\ N_+(r,t) \qquad \ldots (3)$$

$$\frac{dN_+(r,t)}{dt} = p(r) - \alpha_e N_-(r,t)N_+(r,t) - \alpha_i N_+(r,t)N_-(r,t) \qquad \ldots (4)$$

$$\frac{dN_-(r,t)}{dt} = \beta n(r,t) - \alpha_i N_+(r,t)N_-(r,t) \qquad \ldots (5)$$

We assume now and show later (approximations) that under certain conditions $\alpha_e N_+(r,t) \ll \beta$ in equation (3) and in equation (4) for all r, $\alpha_e n(r,t) \ll \alpha_i N_-(r,t)$.

Therefore equations (3) and (4) become

$$\frac{dn(r,t)}{dt} = p(r) - \beta n(r,t) \qquad \ldots (6)$$

and

$$\frac{dN_+(r,t)}{dt} = p(r) - \alpha_i N_+(r,t)N_-(r,t) \qquad \ldots (7)$$

Equation (6) has solution

$$n(r,t) = p(r)\left\{1 - \exp(-\beta t)\right\}/\beta \qquad \ldots (8)$$

For t > say than $3/\beta$, n(r,t)=n(r)=p(r)/β to within 5% in equation (8) and to the same accuracy the right-hand sides of (5) and (7) will become identical. From the conservation of charge and in the body of the ionised gas $N_+(r,t) = N_-(r,t) + n(r,t)$ so that when the electron density reaches equilibrium there will be a constant difference between the values of the ion densities. If we assume that this difference is small compared to the values of the densities, i.e. $p(r)/\beta \ll N_-(r,t)$ then we can make the approximation that $N_+(r,t) = N_-(r,t) = N(r,t)$ where N(r,t) is the average density of either sign of ion at r and t.

Equations (5) and (7) thus become

$$\frac{dN(r,t)}{dt} = p(r) - \alpha_i N(r,t)^2 \qquad \ldots (9)$$

This has solution

$$N(r,t) = \left\{\frac{p(r)}{\alpha_i}\right\}^{\frac{1}{2}} \tanh\left[\left\{p(r)\alpha_i\right\}^{\frac{1}{2}} t\right] \qquad \ldots (10)$$

At equilibrium $N(r,t) = N(r) = \left\{p(r)/\alpha_i\right\}^{\frac{1}{2}}$ $\qquad \ldots (11)$

Rate coefficients

We now consider the values of the various rate coefficients and their variation with air pressure.

Electron attachment

In atmospheric air oxygen and water vapour, but not nitrogen, form negative ions by electron attachment. Chanin, Phelps and Biondi (1962), showed that in the case of oxygen, the attachment process depends on the energy of the attaching electrons. In their experiments electrons were released from a plane surface and then drifted through a tube under the action of an applied d.c. field so that their energy depended on the value of the reduced field E/P where P is the pressure. They found that for E/P<3 Vcm^{-1} $torr^{-1}$ a three-body process is dominant with a P^2 dependence on pressure while for E/P>3 Vcm^{-1} $torr^{-1}$ a two-body process proportional to P operates. In the three-body process, two steps are involved. Firstly a low energy electron collides with a neutral oxygen molecule and forms an excited negative molecular ion. If a third body which may be an oxygen molecule or more probably a nitrogen molecule collides with it before it reverts to its neutral unexcited state by autodetachment of the electron, the excess energy is carried away by this third body to leave the ion in its ground state. The value of the reduced field, E/P, in the Pill-Box varied from ~0·1 to ~0·5 Vcm^{-1} $torr^{-1}$ and according to Chanin, Phelps and Biondi this would correspond to an average electron energy in nitrogen from ~0·2ev to ~0·6ev at which K, the

three-body attachment coefficient in oxygen, goes from $\sim 3{\cdot}5 \times 10^{-30}$ to $\sim 1{\cdot}5 \times 10^{-30}$ cm^6 sec.$^{-1}$ Now $\beta = \sum_x K(x)n(x)n(O_2)$ for the three-body process where x indicates the various components of air, n(x) is the number of molecules per cm^3 of x and $n(O_2)$ is the number of oxygen molecules per cm^3. Over this energy range $K(O_2)/K(N_2)$ varies from 39 to 100. As $n(N_2)/n(O_2) = 3{\cdot}73$, nitrogen makes a contribution to β of from 8·7% to 3·6% and for air at atmospheric pressure $\beta \simeq 10^8$ sec^{-1}.

The same authors show that the reverse process in which the collision between an oxygen molecule and a negative ion leads to electron detachment, can be neglected in comparison with the forward process.

The two-body attachment process depends on the electron having sufficient energy to dissociate the molecule. It is not clear what difference is made when the electrons are produced by the ionisation process where they may have energies of many electron volts as opposed to electrons whose energies are determined by the value of the reduced field.

The radiative attachment process in which the excess energy is carried away by a photon, is too small to be considered here.

Ion-ion recombination

Nawrocki and Papa (1963, pp. 3 - 43, 3 - 44) list a large number of ion-ion recombination reactions in air. From this it is surprising to note that the ones involving O_2 which, from the above discussion on electron attachment, should be the dominant negative species present under the conditions in the Pill-Box, take part only in two-body recombination giving a rate coefficient at least 20 times smaller than the usually accepted value for air. Natanson (1959) gives a theory which covers the low pressure range where a third-body stabilises the encounter between pairs of ions and the high pressure range in which the approach of pairs of oppositely charged ions is governed by mobility. This theory gives a maximum value for α_i of $2{\cdot}42 \times 10^{-6}$ cm^3 sec^{-1} for dry air at normal temperature and just over atmospheric pressure. For pressures greater than one atmosphere α_i is proportional to $\mathbf{P}^{-1}$ and it is sufficiently accurate for our present purpose to take α_i proportional to **P** for $P < 1$.

Electron ion recombination

Electrons and positive ions can combine either by radiative recombination, by dissociation of the resulting molecule or by the three-body process. Only the latter two processes appear to be important in air. Crain (1961) quotes a value of 4×10^{-7} cm^3 sec^{-1} for the dissociative recombination coefficient in nitrogen and $1{\cdot}7 \times 10^{-7}$ cm^3 sec^{-1} at N.T.P. for the three-body process in air which will, of course, be proportional to P. We may expect that below atmospheric pressure $\alpha_e \not< 10^{-7}$ cm^3 sec^{-1}.

Ionic mobility

Mobility is defined as the drift velocity per unit electric field, that an ion acquires in the direction of the electric field. According to Keller, Martin and McDaniel (1965) the term "mobility" is strictly applicable only when one kind of ion whose identity is known is present and when its drift velocity U_i, is proportional to the reduced field; that is, the reduced field is not large enough to give the ion a drift velocity comparable with the thermal velocities of the gas molecules. Even if the latter condition is true for air under Pill-Box conditions, the former certainly is not and there will be present in the ionised air a large variety of mutually interacting ions. On the other hand, if the drift times involved are short enough, effects due to "ageing" of the ions will not occur.

In the literature, measurements are reported mainly for ions drifting in pure gases. In air it is possible to find the following species: O_3^-, O_2^-, O^-, O_2^+, O^+, N_4^+, N_3^+, N_2^+ and N^+. Dalgarno (1962, p.658) quotes a value for the mobility, μ_i, of O_2^+ in O_2 as 2·25cm^{2}V^{-1} sec^{-1}. Chanin, Phelps and Biondi (1962) give 2·7cm^{2}V^{-1} sec^{-1} for O_2^- O_2 in the region of E/P relevant to the Pill-Box. Nawrocki and Papa (1963, pp. 5 - 32, 5 - 33) quote 3·4, 2·6 and 1·9cm^{2}V^{-1} sec^{-1} for O^-, O_3^- and O_2^+ respectively and 2·36 and 1·5 cm^{2}V^{-1} sec^{-1} for N_4^+ and N_2^+ respectively in N_2. Keller, Martin and McDaniel (1965) give a value of 2·47 cm^{2}V^{-1} sec^{-1} for N^+ in N_2. For the present purpose we will take μ_i for air$\simeq$2cm^{2}V^{-1}sec^{-1}. At the low values of E/P relevant to the Pill-Box $\mu_i \propto P^{-1}$.

Electron mobility

In the case of electrons, while there obviously can be no confusion regarding the nature of the charged particle involved, the small mass compared with that of ions means that under the action of an electric field, the electron very readily acquires an energy much greater than the mean thermal energy of the molecules of the gas.

Thus experimentally, it is the drift velocity which is measured as a function of the reduced field and the concept of mobility is not invoked. Crompton, Huxley and Sutton (1953) discuss the motion of slow electrons in air and base their results upon the measurements of Nielson and Bradbury (1937). On the basis of these, the former gives a formula.

$$U_e = 1{\cdot}23 \times 10^6 \, (E/P)^{\frac{1}{2}} \text{ cm sec}^{-1} \qquad \ldots (12)$$

for the drift velocity of electrons in dry air at 15°C, where $0{\cdot}1 < E/P < 0{\cdot}5\ \text{Vcm}^{-1}\ \text{torr}^{-1}$

They also give a formula derived by interpolation of the experimental curve for the region where $E/P < 3 \times 10^{-2}\ \text{Vcm}^{-1}\ \text{torr}^{-1}$

$$U_e = \frac{1{\cdot}59 \times 10^7 E/P}{1 + 33\, E/P}\ \text{cm sec}^{-1} \qquad \ldots (13)$$

and data up to $E/P=20\ \text{Vcm}^{-1}\ \text{torr}^{-1}$. At $E/P=5\ \text{Vcm}^{-1}\ \text{torr}^{-1}$ for example $U_e=2{\cdot}96\times 10^6\ \text{cm sec}^{-1}$, about 5% greater than (13) would give.

At $E/P=20\ \text{Vcm}^{-1}\ \text{torr}^{-1}$, $U_e=8{\cdot}52\times 10^6\ \text{cm sec}^{-1}$.

Air conductivity

We can write the conductivity of the ionised air at r when electrons and ions are close to their equilibrium densities as

$$\sigma(r) = \left\{ p(r) e U_e/\beta E \right\} + \left\{ 2p(r)^{\frac{1}{2}} e \mu_i/\alpha_i^{\frac{1}{2}} \right\} \qquad \ldots (14)$$

where the factor "2" allows for the contributions, assumed equal, of the ions of both signs. Now we have

$$p(r) = \frac{J(r)\, dW/dx}{e\omega} = \frac{I\, dW/dx \exp-(r^2/L^2)}{\pi L^2 e\omega} \qquad \ldots (15)$$

where W is the energy of the electrons in the beam as they pass through the air inside the Pill-Box, dW/dx is their energy loss rate by ionisation and excitation in the direction of the beam x, ω is the average energy loss required to produce an ion-pair in air and e is the charge on the electron.

Therefore using (14) and (15) equation (2) becomes

$$\int_0^\infty 2\pi r\sigma(r)dr = \int_0^\infty \left[\frac{J(r)\, dW/dx\, Ue}{\omega\beta E} + 2\left\{\frac{J(r)\ dW/dxe}{\omega\alpha_i}\right\}^{\frac{1}{2}} \mu_i \right] 2\pi r dr$$

$$= \frac{I\, dW/dx U_e}{\omega\beta E} + 4\left(\frac{\pi L^2 I\, dW/dxe}{\omega\alpha_i}\right)^{\frac{1}{2}} \mu_i$$

$$= d\left(\frac{I}{V} - \frac{1}{R}\right) \qquad \ldots (16)$$

and rearranging (16) we have

$$(1 - V/IR) = \frac{dW/dx\, U_e}{\omega\beta} + 4\left(\frac{\pi L^2 dW/dxe}{\omega\alpha_i I}\right)^{\frac{1}{2}} \mu_i E \qquad \ldots (17)$$

If the ion conductivity is much less than the electron conductivity (17) becomes

$$(1 - V/IR) = \frac{dW/dx\, U_e}{\omega\beta} \qquad \ldots (18)$$

The expression on the left hand side of (18) contains quantities that are, at least in principle, measurable while on the right $\frac{dW/dx}{\omega}$ is known if W is known. We can thus determine U_e/β for the measured values of E and P.

Similarly if the electron conductivity can be ignored in comparison with the ion conductivity, we can determine μ_i^2/α_i. We now compare the values of electron and ion conductivity, first at atmospheric pressure, by evaluating the expressions on the right-hand side of (17).

Evans (1955, pp.582 - 3) gives the expression for the average energy loss rate due to ionisation and excitation for electrons which, for air at N.T.P. and W=5 Mev is $dW/dx = 2{\cdot}3 \times 10^3$ ev cm^{-1} (4·5). An electron can lose up to half of its energy in one collision but this is very rare. However, the average, rather than most probable energy loss, is the correct choice here because of the very large number of electrons in the beam. The most probable loss is the quantity that would normally be involved in measurements of the ionisation caused by a single electron. dW/dx depends directly on the number of electrons/cm^3 which means that, for a given material, it is proportional to P. Evans (1955, p.583) gives the value of ω for air as 32·5 ev. This is independent of pressure. Experimentally for the Pill-Box L=5·5 cm (qv), $I \simeq 0{\cdot}3$ amp and at atmospheric pressure $E \simeq 10^2$ Vcm^{-1} and $e = 1{\cdot}6 \times 10^{-19}$ coulomb. Therefore, $E/P = 0{\cdot}132\ \text{Vcm}^{-1}\ \text{torr}^{-1}$ and from equation (12), $U_e = 4{\cdot}47 \times 10^5\ \text{cm sec}^{-1}$.

$$\text{Therefore } \frac{dW/dxU_e}{\omega\beta} = 3{\cdot}16 \times 10^{-1};$$

$$4\left(\frac{\pi L^2 dW/dxe}{\omega\alpha_i I}\right)^{\frac{1}{2}} \mu_i E = 3{\cdot}09 \times 10^{-2}.$$

That is, at atmospheric pressure, the ions should contribute about 9% to the conductivity.

The dependence of $\frac{dW/dx\ U_e}{\omega\beta}$ on E and P is $E^{\frac{1}{2}}P^{-\frac{3}{2}}$ for all P while $4\left(\frac{\pi L^2 dW/dxe}{\omega\alpha_i I}\right)^{\frac{1}{2}} \mu_i E$ has a dependence EP^{-1} for $P>1$ and E for $P<1$.

Experimentally, except for the lowest pressures, E increases with P. For $P<1$ the ratio of electron to ion conductivity has a dependence $(EP)^{-\frac{1}{2}}$ and for $P>1$, $(EP^3)^{-\frac{1}{2}}$. It is, therefore, clear that the

relative ion contribution to the conductivity increases as P increases and will become important at the highest pressures.

Approximations

The treatment of the theory of the Pill-Box has involved several approximations whose validity we now examne to determine over what range of pressure they hold good.

First we look at the inequalities. In equations (3) and (4) we required $\alpha_e N_+(r,t) << \beta$ and $\alpha_e n(r,t) << \alpha_i N_-(r,t)$. These are identical for $N_+(r,t) = N_-(r,t)$. If the first inequality is true for the maximum value of $N(r,t)$, $N(o)$, it will be true for all r and t. We will take " $>>$ " to mean " $>$ 20 times ". That is, we require $\beta > 20\alpha_e N(o)$. Using the previously discussed values, $\beta = 10^8$ sec^{-1}

and $20\alpha_e N(o) = 20\alpha_e \left(\frac{I\,dW/dx}{\pi L^2 e\omega\alpha_i}\right)^{\frac{1}{2}} = 2{\cdot}6 \times 10^6$ sec^{-1}

so that the inequality is valid at atmospheric pressure. Inserting the dependencies on pressure previously discussed, we requirc $P > 2{\cdot}6 \times 10^{-2}$ atmosphere or 20 torr. For $N_+(o) \simeq N_-(o)$ we

require $\beta > 20 \left(\frac{I\,dW/dx\,\alpha_i}{\pi L^2 e\omega}\right)^{\frac{1}{2}} = 3{\cdot}68 \times 10^7$ sec^{-1}.

This is satisfied for $P > 1$. For $P < 1$, we require $P > 0{\cdot}37$ atmospherc or 280 torr.

For the electron population to reach equilibrium, we required $\beta > 3/\tau$ and if $\tau = 4 \times 10^{-6}$ scc, then β must be greater than $7{\cdot}5 \times 10^5$ sec^{-1}. This implies $P^2 > 7{\cdot}5 \times 10^{-3}$ or $P > 8{\cdot}7 \times 10^{-2}$ atmosphere or 66 torr.

For the ion population to reach within 5% of equilibrium, we require $\left\{ p(r)\alpha_i \right\}^{\frac{1}{2}} \tau > 1{\cdot}8$ from (10). This clearly will not be satisfied for all r but for r=o it is satisfied for $P > 0{\cdot}25$ atmosphere or 190 torr. As we have previously shown that the ion conductivity is small for $P \not> 1$, the non-equilibrium of the ion population at low pressure is not important.

We have still to demonstrate that the Pill-Box considered as a resistance-capacitance combination, will be nearly fully charged at thc end of the electron pulse, assuming that the ion and electron population have reached their maximum values.

That is, $R_g RC/(R_g + R) < \tau/3$ for 95% of maximum charge.

That is $R_g < 1/\left(\frac{3C}{\tau} - \frac{1}{R}\right)$. Experimentally the largest value of R was $10^4\Omega$ and $C \simeq 2 \times 10^{-10}$F. Therefore, we require $R_g < 2 \times 10^4\Omega$

$$\text{Now } \frac{1}{R_g} = \int_0^\infty \frac{2\pi r\sigma(r)dr}{d} = \frac{I\,dW/dx\,U_e}{\omega\beta E d} + 4\left(\frac{\pi L^2 I\,dW/dxe}{\omega\alpha_i}\right)^{\frac{1}{2}} \frac{\mu_i}{d}$$

from (16). Experimentally, $d \simeq 2$ cm and from our previous results at $P = 1$, $R_g = 1{\cdot}92 \times 10^3\Omega$. Now R_g will increase as P increases but as the ion conductivity is constant for $P > 1$ the maximum value of $R_g \simeq 2 \times 10^4\Omega$ regardless of the behaviour of the electron conductivity. On the other hand R_g will decrease with decreasing pressure for $P < 1$.

Sheath effects

In the treatment so far it has been tacitly assumed that the properties of the ionised gas are uniform in the direction of the electron beam. It is shown later that the electron emission from the central negatively charged plate is very small and therefore there is a region next to this plate in which the electron density decreases from its value in the body of the gas to almost zero at the plate. The thickness of this sheath region, s, will be of thc order of the mean distance between electrons, $n(r)^{-\frac{1}{3}}$, assuming that the electron density is less than the ion density which is true down to $P \simeq 14$ torr. Across this region the current will be carried by the ions which, if they havc a smaller conductivity than that due to the electrons in the bulk of the gas, will require a larger electric field. It is important to determine the magnitude of the voltage drop, V_s across the sheath in comparison with the voltage drop across the Pill-Box. Assuming the absence of negative ions in the sheath we have from (16) and neglecting R.

$$I \simeq 2V_s \left(\frac{\pi L^2 I dW/dxe}{\omega\alpha_i}\right)^{\frac{1}{2}} \frac{\mu_i}{s}$$

$$\text{and } s = \left(\frac{\pi L^2 e\omega\beta}{I\,dW/dx}\right)^{\frac{1}{3}} \simeq 4 \times 10^{-4}\text{cm}$$

$$\text{Therefore, } V_s = \tfrac{1}{2}\left(\frac{I}{\pi L^2 e}\right)^{\frac{1}{6}} \left(\frac{\omega}{dW/dx}\right)^{\frac{5}{6}} \frac{\alpha_i^{\frac{1}{2}}\beta^{\frac{1}{3}}}{\mu_i}$$

$\simeq 2{\cdot}7$ volt at $P = 1$ atmospherc.

The dependence of V_s on P is $P^{\frac{1}{4}}$ for $P < 1$ and $P^{\frac{5}{3}}$ for $P < 1$. This voltage drop is due to the reduced conductivity in the sheath. However, if the sheath is a region where there are no negative charges, there will also be a voltage drop across it due to space charge effects. Using the appropriate units Poisson's equation is:

$$\frac{d^2V}{dx^2} = -4\pi N_+(o)e \text{ at } r = o \qquad \ldots (19)$$

and the equation of continuity:

$$I = \pi L^2 N_+(o) e\mu_i \frac{dV}{dx} \qquad \ldots (20)$$

By eliminating $N_+(o)$ from (19) and (20) by substitution and integrating twice with the boundary conditions that $\frac{dV}{dx}=o$, $V=o$ at $x=s$ we obtain

$$V_s=\frac{2}{3}\left(\frac{8\pi I}{\pi L^2\mu_I}\right)^{\frac{1}{2}} s^{\frac{3}{2}}=\frac{2}{3}\left(\frac{8\pi e\omega\beta}{\mu_i\, dW/dx}\right)^{\frac{1}{2}}$$

using the previous expression for s. Inserting the appropriate values we get $V_s\simeq 0{\cdot}1$ volt. Here there is a P pressure dependence. It is therefore clear that we are justified in ignoring sheath effects over the whole pressure range.

Diffusion

It has also been assumed, so far, that the electron density distribution in the ionised air has a one to one correspondence with the ionising rate as a function of r and that the distribution of ions and electrons at equilbrium is maintained throughout the duration of the electron pulse. Now the conduction electrons in their random motions move very much faster than the ions and so will tend to escape radially from the ionised volume. In so doing a radial electric field will be established which opposes this net drift. Positive ions will move under the action of this field and drag with them the negative ions. Thus, the whole distribution will spread out a rate governed by the ion mobility. This is called ambipolar diffusion. Loeb (1955, p.209) gives an expression for the ambipolar diffusion coefficient when electrons, positive and negative are present:

$$D_a=\frac{g(\mu_i^+D_e+\mu_eD_i^+)+(1-g)\ (\mu_i^+D_i^-+\mu_i^-D_i^+)}{\mu_i^+ +\{g\mu_e+(1-g)\mu_i^-\}} \quad . . . (21)$$

where the ratio of electron density to negative ion density is $g/(1-g)$ and where μ_e, μ_i^-, μ_i^+ and D_e, D_i^-, D_i^+ are the mobilities and diffusion coefficients of electrons, negative and positive ions respectively. $\mu_i^+/D_i^+=\mu_i^-/D_i^-=e/kT_e$ where k is Boltzmann's constant and T is the absolute temperature of the ions, assumed to be the same as that of the gas. Again, it will be sufficiently accurate for the present purpose to take $\mu_i^+=\mu_i^-=\mu_I$. Also $\mu_e/D_e=e/kT_e$ where T_e is the electron temperature. At P=1, $g\simeq 1{\cdot}8\times10^{-2}$ so that $1-g\simeq 1$ and if $T_e\simeq T$ we can write

$$D_a\simeq 2\mu_I\frac{kT}{e}\left(\frac{\mu_I+g\mu_e}{2\mu_I+g\mu_e}\right) \quad . . . (22)$$

If we differentiate the expression in (13) with respect of E and let E/P tend to zero, we obtain the electron mobility at very small reduced field. This gives $\mu_e=2\times10^4/P\,cm^2V^{-1}sec^{-1}$, P in atmos., and therefore we see that at P=1, $\mu_I<<g\mu_e$ and $D_a\simeq 2\mu_I\frac{kT}{e}$ which at T=300°K gives $D_a\simeq 0{\cdot}1$ $cm^2\ sec^{-1}$.

It is possible to see whether ambipolar diffusion is important at atmospheric pressure by evaluating the time for the distribution to diffuse a distance L. This is of the order $L^2/D_a\simeq 3\times10^2$ sec compared to $\tau=4\times10^{-6}$ sec. It is therefore clear that in spite of the approximate nature of the treatment and for all pressure of interest, diffusion effects are negligible.

Electron emission

Electron emission from the central plate under the bombardment of the electron beam has not been considered so far. Wright and Trump (1962) discussed the back-scattering of megavolt electrons from thick targets and divided it into two kinds. They associated electrons emerging from the surface with energies of less than 50 eV with secondary emission and those with energies greater than 50 eV as electrons back-scattered by elastic and in-elastic nuclear collisions and by close electron-electron encounters. From the point of view of the Pill-Box, both groups will reduce the charging rate, while only the higher energy one will contribute to to the ionisation of the gas. They give for 2 MeV electrons incident on aluminium a secondary emission of 3% and a back-scatter fraction of 5%. By extrapolation the back-scatter fraction at 5 MeV is less than 1%. At 3 MeV the average energy of the back-scattered electrons from aluminium is 1·2 MeV. Thus we conclude that those two types of electron emission can be neglected for our present purpose. The absorption of the 5 MeV electron beam in the central plate and block will produce X-rays which can contribute to electron emission by ejecting Compton electrons from the aluminium casing of the block. Due to the large mass of lead in the block acting as a shield, this effect is thought to be quite negligible.

Nawrocki and Papa (1963, pp.8 - 39, 8 - 41), indicate that the efficiency with which energetic electrons produce fluorescent photons in air at atmospheric pressure is less than 1%. If the photons have energy of about 3eV this means that each fast electron in passing through the Pill-Box will produce less than 10 photons. The photo-electric effect is not likely to have a quantum efficiency of greater than 1% on the unprepared surface of the central plate. It is clear, therefore, that photo-emission as well can be ignored in considerations of the Pill-Box charging rate.

Discharge of the Pill-Box

We now consider the discharge of the Pill-Box after the cessation of the electron pulse. The condition for the electron population at equilibrium during the charging phase to be negligible compared to the ion population is the same as that

for the mean lifetime of the ions to be much greater than that of the electrons. If we consider pressures where these conditions hold, then the electron population will disappear by attachment before there is any appreciable change in the Pill-Box voltage or ion population. It has already been demonstrated that diffusion effects are not important during the charging phase and this will be equally true during the discharge phase. The situation is therefore that of the discharge of the Pill-Box capacity through the resistance of a re-combining ion plasma.

Let t^1 be the time measured from the beginning of the discharge. As before N(r) is the density of ions of either sign at $t^1=o$ and now $N(r,t^1)$ is the density of ions of either sign at r and t^2.

Then we have: $$\frac{dN(r,t^1)}{dt^1} = -\alpha_i N(r,t^1)^2 \quad \ldots (23)$$

which has solution:

$$N(r,t^1)=1/\{\alpha_i t^1+1/N(r)\} \quad \ldots (24)$$

Therefore $\sigma(r,t^1)=2e\mu_i/\{\alpha_i t^1+1/N(r)\}$ ... (25)

where $\sigma(r,t^1)$ is the conductivity at r and t^1 and the equation for the discharge is

$$C\frac{dV(t^1)}{dt^1} = -\frac{V(t^1)}{d}\int_o^\infty 2\pi r\sigma(r,t^1)dr - \frac{V(t^1)}{R} \quad \ldots (26)$$

where $V(t^1)$ is the Pill-Box voltage at t^1.

From (11) and (15) we have $N(r)=\left(\frac{I\ dW/dx}{\pi L^2 e\omega\alpha_i}\right)^{\frac{1}{2}}$ $\exp-(r^2/2L^2)$ and substituting this expression into (25) and integrating (26) with respect to r, we have

$$\frac{V(t^1)}{V(o)}=\exp-\left[\frac{4\pi e\mu_i L^2}{dC\alpha_i} \text{ x } \int_o^\infty \frac{\log\{1+\alpha_i\left(\frac{I\ dW/dx}{\pi L^2 e\omega\alpha_i}\right)^{\frac{1}{2}} t^1\}dt^1}{t^1} + \frac{t_1}{RC}\right] \quad \ldots (27)$$

where V(o) is the voltage at $t^1=o$.

The integration with respect to t^1 in (27) cannot be performed analytically.

If the oscillograph trace, produced experimentally, of the discharge of the Pill-Box is assumed to be of the form (27), then in principle if d, R, C, I, L, and dW/dx and ω are known, it is possible to deduce μ_i and α_i by unfolding this function of t^1 by computer analysis.

Let $f(t^1)$ be the function produced by operating on $V(t^1)/V(o)$ with

$$1/\frac{d}{dt^1}\left[\left\{-\frac{d}{dt^1}\log V(t^1)-\frac{1}{RC}\right\} t^1\right]$$

That is, $f(t^1)=$

$$\frac{dC}{4\mu_i}\left(\frac{\omega\alpha_i}{I\ dW/dx\ \pi L^2 c}\right)^{\frac{1}{2}} \left\{1+\alpha_i\left(\frac{I\ dW/dx}{\pi L^2 e\omega\alpha_i}\right)^{\frac{1}{2}} t^1\right\} \quad \ldots (28)$$

which is a linear function of time.

Therefore, for $t^1=o$

$$f(t^1)=\frac{dC}{4}\left(\frac{\omega}{I\ dW/dx\ \pi L^2 e}\right)^{\frac{1}{2}}\left(\frac{\alpha_i}{\mu_i}\right)^{\frac{1}{2}} \quad \ldots (29)$$

and $$\frac{df(t^1)}{dt^1} = \frac{dC}{4\pi L^2 e}\left(\frac{\alpha_i}{\mu_i}\right)$$

That is, if the computer analysis produces a straight line, μ_i and α_i can be found from the slope and the intercept at zero time.

Pill-Box

The Pill-Box condenser was carried on a steel framework mounted on rubber tyred wheels for ease of movement. Its position in relation to the accelerator window and to the nominal direction of the electron beam was fixed by lining up centring pins at the front and rear of the framework on a line ruled on the floor. The Pill-Box was made of three aluminium alloy octagonal rings bolted together to form a cylindrical housing of internal diameter 60 cm and length 30 cm. A hollow aluminium alloy vessel, 20 cm long and 20 cm diameter, filled with lead keyed into an internal spiral groove was supported coaxially in the housing by three S.R.B.F. spokes. This block served as a beam trap for the high energy electrons and the resulting Bremsstrahlung radiation. Electrical connection was made to it by means of an aluminium rod screwed into the block and passed through the vertical spoke to the outside via a cylindrical Perspex insulator. Aluminum alloy plates were bolted to either end of the housing. The rear one was merely an electrical screen. The front one, which served as the thin plate of the parallel plate condenser, was $1\frac{3}{8}$ in thick, its inside surface was machined flat to 5 thousandths of an in, and its outside surface contained a recess 10 in in diameter and 1 in deep to define the maximum cross-section of the electron beam. An 'O' ring, held in a groove machined in the end face of the housing made a vacuum/pressure seal with the front cover. The thick plate of the condenser was an aluminium alloy disc, 50 cm in diameter and $\frac{7}{8}$ in thick and machined flat to one thousandth of an inch. Its back surface has a threaded recess 9 in in diameter, carrying 20 threads to the inch which mated with a threaded ring, secured by three recessed grub screws to the block. Thus the plates of the condenser could be made accurately parallel to each other and the distance between them varied. The dimensions of this condenser

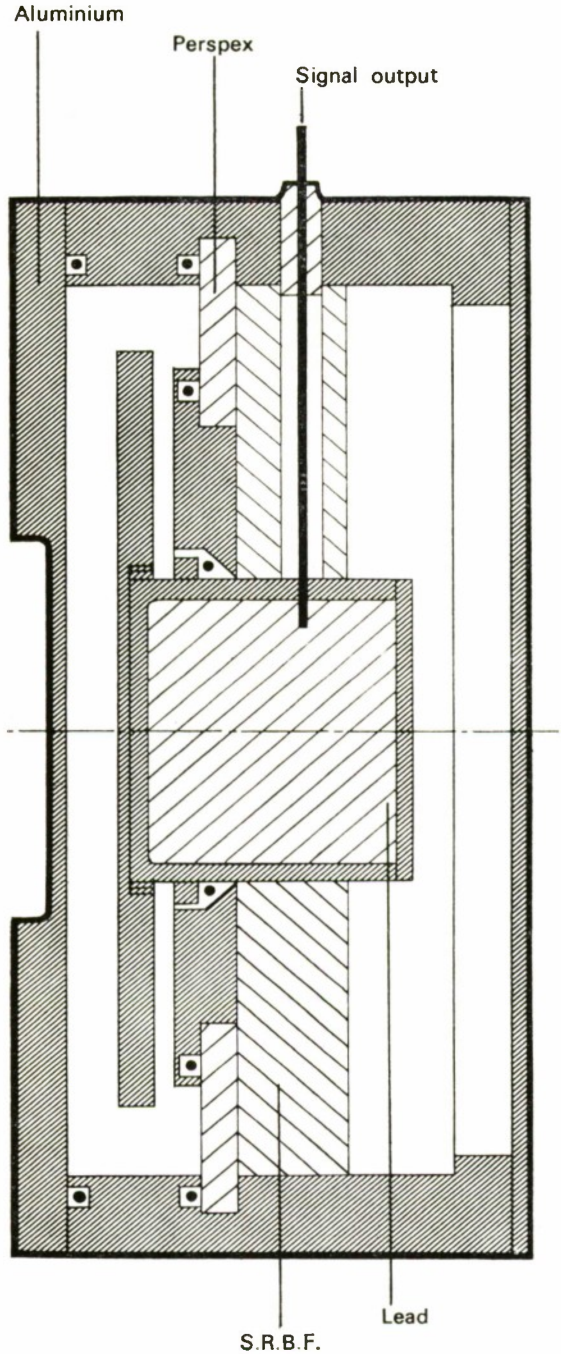

FIG. 1. Sectional side elevation of Pill-Box.

were such that it was a very good approximation to regard the electric field between the plates as constant in any plane parellel to the plates.

A vacuum/pressure seal between the block and the housing was made in two parts. An annular aluminium alloy plate was fixed to the block behind the thick plate by means of a compression 'O' ring seal and an annular Perspex plate in turn was secured on its inner diameter to it and on its outer diameter to the Pill-Box housing by further 'O' ring seals. This arrangement ensured that the Perspex was not in the path of the electron beam. The sealed volume could thus be evacuated or pressurised. This arrangement is shown in Fig. 1 and in the photograph in Fig. 2 which shows the front cover removed and the interior of the Pill-Box.

The gas system consisted of a two-stage backing pump, an oil-free gas circulator, a dryer unit filled with molecular sieve, and the associated pipe work and valves some of which were manual and others remotely operated magnetic.

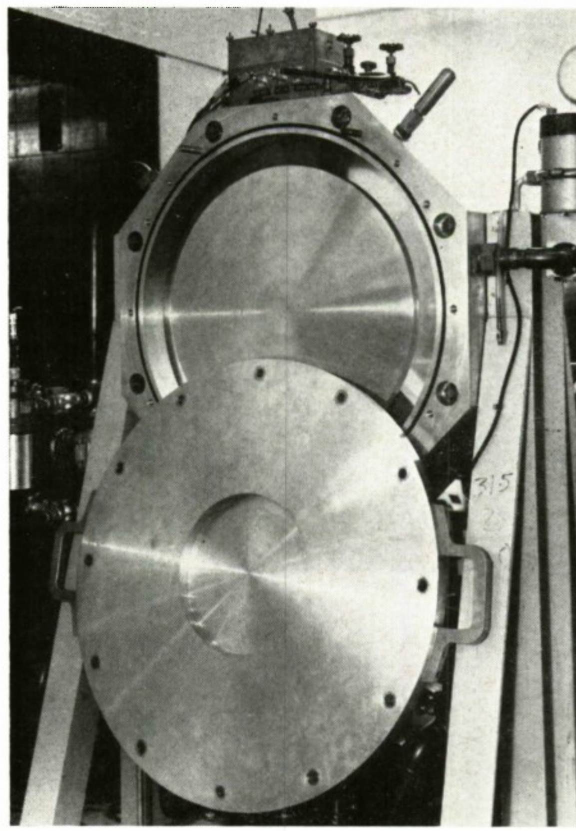

FIG. 2. Pill-Box with front plate removed.

Gas pressure above atmospheric was measured on a Bourdon gauge, viewed by closed-circuit television. Below atmospheric, a capsule gauge, again viewed by television, and a LKV Autovac Pirani type gauge were used. The gas humidity was monitored with a Shaw Hygrometer unit and checked by means of a Birlec Dewpointer. Except for the experiments at high humidity, air from commercial cylinders was used to fill the Pill-Box. The interior of the Pill-Box was cleaned with Inhibisol.

Signals from the Pill-Box were conveyed to the recording equipment in the accelerator control room by 60 ft of UR70 cable. A similar cable was used for the accelerator secondary emission monitor. A metal screening box on top of the Pill-Box housing over the previously mentioned cylindrical Perspex insulator contained a set of prevision resistors mounted on a rotary switch which could be operated remotely. Thus the Pill-Box output could be connected to the signal cable either directly or in series via one of these resistors. A facility was also incorporated for applying either d.c. or square pulses to the system for calibration purposes.

The recording system consisted of a pair of transistorised oscillographs, A.W.R.E. type T4214A, one for the Pill-Box and the other for the secondary emission monitor, both terminated with nominally 72 ohm resistors. Each was fitted with a Telford camera and a Polaroid film back and all records were made either on Polaroid 46L projection film or Polaroid 3000 picture roll film. Timing information on the records was in the form of trace intensity modulation at 10 Mc/s provided by a Tektronix Timemark generator. D.C. calibration of the Pill-Box oscillograph on all sensitivity ranges and up to the maximum deflection was performed with an International Electronics stabilised d.c. voltage supply and a Solartron digital voltmeter. The overall pulse response of the system was set up by using a Nagard pulse generator and adjusting trimmers on the oscillograph input attenuator. The oscillograph time bases were tripped from the accelerator control circuit.

Linear accelerator

The electron beam in these experiments was provided by the Vickers 15 Mev linear accelerator. This machine could provide pulses of electrons up to 4μsec in duration and a maximum peak current of about 300 mA. For safety and interference reasons pulse repetition rates of 10 p/sec and 1 p/sec only were available (and sometimes only the latter). The former rate produced the most stable results. The rise and fall times of the pulses were about 1/3 μsec and with suitable adjustment of the many inter-acting controls reasonably flat topped pulses could be obtained.

The secondary emission monitor was a one thousandth of an inch titanium foil and the electron beam passed through this and then through a five thousandths of an inch titanium foil before emerging into the air. Some 3% of the beam current was intercepted by the monitor.

Experimental procedure

In the main series of results each experimental point was the result of the measurements on two Pill-Box oscillograms. In the "current" measurement the Pill-Box was connected directly to the cable and before the photograph was taken the accelerator was run and adjusted to give the biggest and flattest topped pulse, as judged by eye, on the oscillograph screen. For the "voltage" measurement the same conditions in the Pill-Box and accelerator were maintained except that the Pill-Box was now connected to the cable via a series resistor, selected remotely, which was the largest compatible with a steady and flat-topped trace. In practice these were either 51kΩ, 10kΩ, or 5·1kΩ. The oscillograph deflection sensitivity control was then switched to give the largest trace height inside the usable oscillograph screen area. The secondary emission monitor current was recorded on each occasion, the assumption being that it was proportional to the Pill-Box current and thus any drift in the value of the accelerator current between the two measurements could be allowed for.

At 10 p/sec a 1/5 second camera exposure ensured that at least one pulse would be recorded. At 1 p/sec the shutters were held open and the accelerator switched on and off in quick succession to catch only one pulse. The "one shot" control on the accelerator was unreliable. When 10 p/sec was required but external restrictions prevented its use, the accelerator was set up on 1 p/sec and momentarily switched to the higher rate for the recording. After the "voltage" measurement a base line was recorded on the same film by switching out the oscillograph input, opening the camera shutter and tripping the oscillograph time base. The oscillograph time bases were set at 1 μsec/cm. In all the experiments reported here, the gas was at or near room temperature of 20°C.

Records made on transparency film were analysed on an Aeronautical and General Instruments film assessor and digitisor (A.G.I.) which projected a magnified image of the trace on to a ground-glass screen carrying cross-wires. With the A.G.I. correctly lined up for each film, the height of any point on the trace above its base line and its time coordinate were indicated on a digital display. Alternatively, in the cases of some of the Pill-Box voltage decay curves the heights of successive points at intervals of 0·1 μsec were directly punched on to I.B.M. computer cards. The records on positive prints were measured with a ruler and set square.

The Pill-Box "current" trace heights were measured at three points 1 μsec apart and an average value calculated. The Pill-Box "voltage trace heights were measured at two points; one immediately before the start of the decay and the other 1 μsec earlier. In practice the relative difference

between them was never more than 3% and in most cases considerably less. The former height was taken as the value for calculation.

The secondary emission waveforms were "noisy". However, the flattest part was selected for each pair and the measurements made at points occurring at the same time from the start of the pulse.

Because of the marked non-linearity of oscillograph deflection against voltage, deflections were measured against known, d.c. voltages up to the maximum usable deflection for all sensitivity ranges and all trace measurements were corrected from the calibration curves thus produced.

The Pill-Box termination resistance was measured *in situ* by comparing the voltages across it and a known precision resistor connected in series with it to a stabilised d.c. power supply. Its value was 68·0Ω. The usual separation between the Pill-Box plates was measured to be 2·027 cm. At this spacing the capacitance of the Pill-Box was measured, using a Rohde and Schwartz Karu type bridge, to be 206 pF. The variation of capacitance over the pressure range from 3 atmospheres to 25 mtorr was about 2% so that it could reasonably be assumed that the distance between the plates was constant to this accuracy.

Variation of Pill-Box voltage with plate separation

The variation of Pill-Box voltage with plate separation was investigated using atmospheric air at N.T.P. "Voltage" oscillograms were recorded for a series of central plate positions produced by rotating the plate on the threaded ring. In this experiment an earlier version of central plate was used, the only significant difference being that it gave a smaller maximum plate separation. The actual plate separation was measured with the front plate removed by means of a dial gauge and straight edge at three points on the central plate. The Pill-Box voltage was corrected for the effect of the external resistance and it is shown plotted against plate separation in Fig. 3. The line drawn through the points is a "least squares fit" and demonstrates the linear relationhip between Pill-Box "open-circuit" voltage and separation.

Variation of Pill-box voltage with pressure and humidity

The main part of these experiments was to measure the effect of pressure on the Pill-Box voltage and to compare this with the theoretically predicted relationship between them.

The Bourdon gauge used for measuring pressures above atmospheric was not calibrated but should have been accurate to within $1\frac{1}{2}$% of full scale deflection. The Autovac and capsule gauges used below atmospheric pressure were compared with a McLeod gauge and the agreement was reasonable in relation to other experimental errors. At the lowest pressure achieved in the Pill-Box, 25 mtorr, there was no evidence that the impact of the electron beam on the central plate caused any out-gassing. Measurements on very dry air were made from 25 torr up to ~3 atmospheres. The air below 25 torr could not be kept dry because of leakage into the Pill-Box from the atmosphere. The procedure in the dry air measurements was to fill the evacuated system at high pressure from commercial air cylinders via a reducing valve and to circulate the gas through the dryer unit until a dew point of ~ −100°C, equivalent to less than 1 part of moisture per million, was indicated on the Shaw-meter. This took about 1 hour. The measurements were then made at successively reduced pressure with the circulator in operation. Below 25 torr the circulator was switched off and isolated and the

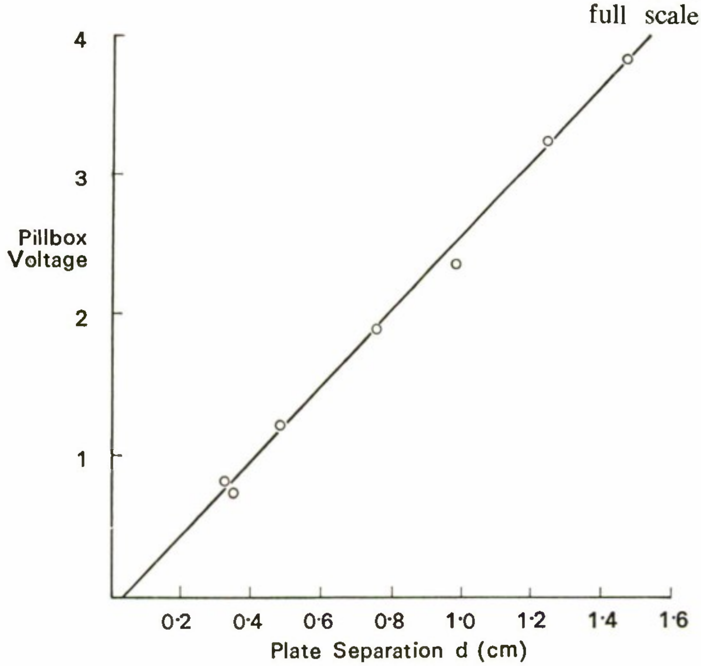

FIG. 3. Pill-Box voltage as a function of separation between the plates.
Voltage on an arbitrary scale, plate separation in centimetres.

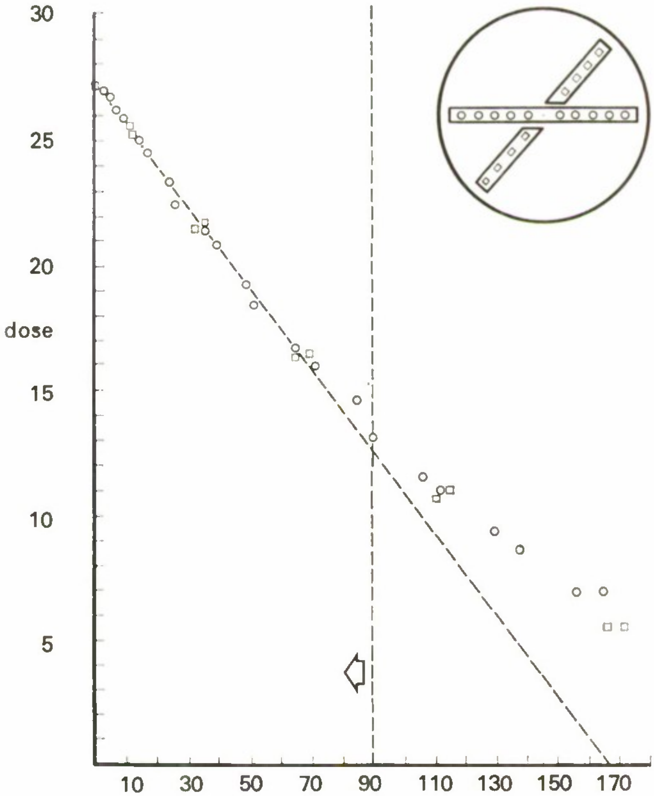

FIG. 4. Electron beam profile. Plot of logarithm of the corrected dose on an arbitrary scale as measured using lithium fluoride thermoluminescence against the square of the distance from the peak of the distribution in square centimetres.
The dotted line represents a Gaussian distribution and 95% of the beam current is included by it.
The key indicates the position of the samples on the Pill-Box central plate.

vacuum pump operated directly on the Pill-Box. In the experiments with moist atmospheric air, the humidity was measured on the Birlec dew-pointer and checked with a whirling hygrometer. These measurements are presented and discussed later.

Beam profile

The electron beam current density profile inside the Pill-Box was measured. Some preliminary experiments involving long irradiations indicated that the principal direction of the beam swept out an elliptical area so that to obtain a meaningful result a method sensitive to one pulse was required. The method used employed thermoluminescence dosimetry. Fifty samples of 30 mg quantities of lithium fluoride powder contained in coded polythene bottles 1·5 cm long and 0·5 cm diameter were fixed to a circle of cardboard in arrays along two diameters at 45°. This was secured to the central plate of the Pill-Box and the front cover replaced. One machine pulse was produced and the current oscillogram recorded in the usual way. The sample doses were measured on a CON-RAD reader by the Health Physics group at A.W.R.E. It was suspected that this dosimetry system might be non-linear at the dose levels involved due to a transition from the region where the thermoluminescence is due to naturally occurring trapping centres to the region where the centres are produced by the radiation itself. In order to correct for this a calibration run was necessary. The Pill-Box was placed 3 metres from the accelerator window so that about 40 pulses were required to give the same dose as did a single pulse previously at any point. Samples were placed one at a time at the centre of the front plate and were irradiated with from two to two hundred pulses, the actual number being counted on a Scalar unit connected to Pill-Box output. Oscillograms of the Pill-Box current were recorded during each run and the areas under each trace, as measured with a planimeter, were multiplied by the corresponding number of pulses to give the correct relative dose. This was plotted against the dose as measured on the sample to give a calibration curve. It should be noted that beam profile was so broad at 3 metres that changes in beam direction previously mentioned could be ignored.

The original profile measurements were then corrected using the calibration curve and plotted against distance from the Pill-Box axis. The centre of the distribution, which did not lie on this axis, was found by comparing both halves of it visually

until the centre of symmetry was obtained. The natural logarithm of the dose was plotted against the square of the distance from this centre. (Fig. 4).

Measurement of the slope of the straight part of this curve gave the characteristic dimension, L, $=5{\cdot}5$ cm. 95% of the current included in the area out to $r^2=90$ cm^2 is thus quite accurately described by a Gaussian distribution. This profile represented the distribution when the Pill-Box front cover was 50 cm from the accelerator window which was the distance used for all experiments except for two measurements at 3 metres and 7 cm.

Beam energy

Calculation of the ionisation rate in the gas volume requires that dW/dx be known and this in turn depends on the electron beam energy inside the Pill-Box, W. The accelerator was nominally a 15Mev machine but at the time the energy had not been independently measured. The energy depends on the beam current as well as on other parameters which were held constant during these experiments, unless otherwise stated, so that the energy should have been nearly constant. In fact, dW/dx is not a very sensitive function of W in this energy region. A measurement was made of W by the transmission method as follows. Pill-Box "current" oscillograms were recorded for varying thicknesses of absorber in the form of aluminium alloy discs, 0·0865 cm thick, which just fitted into the recess in the front plate of the Pill-Box. The traces were measured in the usual way, the pulse heights being corrected for non-linearity of the oscillograph deflection sensitivity and normalised to a constant value of secondary emission monitor current. The resulting voltages are shown plotted against thickness of aluminium alloy absorber in Fig. 5. The point at zero thickness was measured with the Pill-Box front cover removed. The other points represent varying thicknesses of absorber consisting of the front cover only up to the front cover plus one to 14 discs. Runs were done at near atmospheric pressure and at 30 mtorr and the close agreement between them implies that the greater majority of the current flowed in the external terminating resistance. The interaction between accelerator energy and current is shown by the effect of lowering the current. At the end of the electron range the resulting increase in electron energy caused a marked increase in the normalised Pill-Box voltage whereas at 0·95 cm of aluminium alloy the effect was hardly significant. The shape of the curve is similar to that shown by Evans (1955, pp.622 - 625) for the range-energy relation for monoenergetic electrons. The extrapolated range, Xo, which is the point at which the extension of the straight part of the graph cuts the absorber thickness axis is equal to 2 cm or 5·4 g cm^{-2} for an alloy density of about 2·7 g cm^{-3}.

From the empirical formula given by Evans.

Xo (mg cm^{-2})$=530\,E-106$ where 1 Mev$<E<20$ Mev and E is the initial electron kinetic energy in Mev, $E=10{\cdot}4$ Mev. In the usual mode of operation of the Pill-Box, the beam had to penetrate 0·95 cm of aluminium alloy in the front cover and as $Xo \propto E$ in the above energy range (Evans 1955, pp.622 - 625) the energy of the electron beam inside the Pill-Box, W is given by

$$W=E-\frac{0{\cdot}95\times2{\cdot}7\times10^3+1{\cdot}06\times10^2}{5{\cdot}3\times10^2}\text{ Mev}$$

$$=5{\cdot}4\text{ Mev}$$

Calculation of results

The voltage across the oscillograph termination at equilibrium in the "voltage" measurement, V_m, was calculated by multiplying the trace height

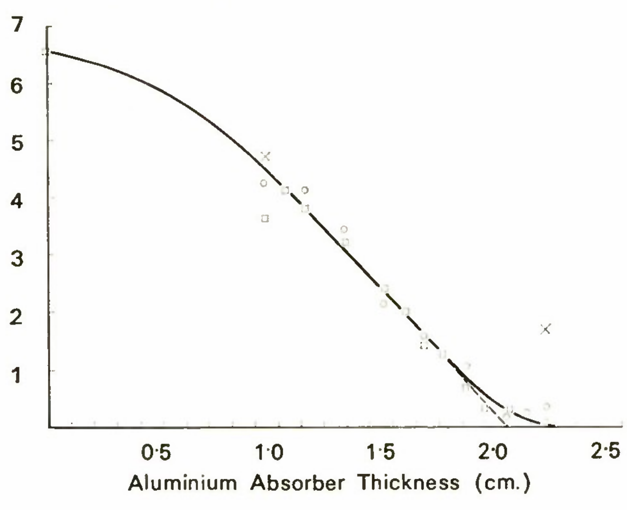

FIG. 5. Electron beam energy. Plot of Pill-Box current on arbitrary scale against thickness of aluminium alloy absorber in centimetres Intercept of dotted line on axis gives the extrapolated range. Points enclosed by circles were made at a pressure between 29 and 45 mtorr, those by squares at atmospheric pressure and those indicated by crosses at higher beam energy and lower beam current.

by the corresponding deflection sensitivity. The Pill-Box voltage is then given by $V=V_mR/R_T$ where R_T is the resistance of the termination. The voltage across the termination during the "current" measurement, Vc was calculated in a similar manner. From equation (16) and the definition of R_g we can write

$$I=V\left(\frac{1}{R_g}+\frac{1}{R}\right)$$

and

$$I_c=V_c\left(\frac{1}{R_{gc}}+\frac{1}{R_T}\right) \qquad \ldots (30)$$

$$\ldots (31)$$

where I_c and R_{gc} are the beam current and gas resistance respectively during the "current" measurement. It is assumed that $I_c=\eta$ I where η is the ratio of secondary emission monitor oscillograph deflections for each pair of measurements. Now the gas resistance is an increasing function of the Pill-Box electric field so that in general R_{gc} is considerably smaller than R_g. Also it is not always sufficiently accurate to neglect $1/R_{gc}$ in comparison with $\frac{1}{R_T}$ so that an approximate method has to be used to determine I. If R_g and R_{gc} are taken to be equal and eliminated from equation (30) and (31) we have

$$I\simeq\left(\frac{1}{R_T}-\frac{1}{R}\right)\Big/\left(\frac{\eta}{V_c}-\frac{1}{V}\right)$$

and substituting for I in (30)

$$\frac{1}{R_g}=\left(\frac{R}{R_T}-\frac{\eta V}{V_c}\right)\Big/\left(\frac{\eta V}{V_c}-1\right)R$$

Therefore we have

$$\frac{1}{IR_g}\simeq\left(\frac{R}{R_T}-\frac{\eta V}{V_c}\right)\Big/\left(\frac{R}{R_T}-1\right)V \qquad \ldots (32)$$

We note that the above will make I larger than its correct value and R_g smaller so that I/IR_g will tend to be a good approximation. We can rewrite equation (16) by dividing by 1/Id as:

$$\frac{1}{IR_g}=\frac{dW/dx\ U_e}{\omega\beta V}+\frac{4\mu_1}{d}\left(\frac{\pi L^2 dW/dx\ e}{\omega\alpha_1 I}\right)^{\frac{1}{2}} \qquad \ldots (33)$$

If the expresson given in (12) is written as $U_e=a\,V^{\frac{1}{2}}$

where $a=1{\cdot}23\times10^6/(dP)^{\frac{1}{2}}$ cm sec^{-1}volt$^{-\frac{1}{2}}$ ... (34)

then on multiplying (33) by $V^{\frac{1}{2}}$ we have from (32)

$$\left(\frac{R}{R_T}-\frac{\eta V}{V_c}\right)\Big/\left(\frac{R}{R_T}-1\right)V^{\frac{1}{2}}=\frac{dW/dx\ a}{\omega\beta}+4\frac{\mu_1}{d}\left(\frac{\pi L^2 dW/dx\ eV}{\omega\alpha_1 I}\right)^{\frac{1}{2}} \qquad \ldots (35)$$

The usefulness of the above expression is that for pressures where the ion conductivity is negligible it should be a simple function of pressure and independent of Pill-Box current or electric field. It is plotted as a function of air pressure on a log-log scale in Fig. 6.

Results and Discussion

It can be seen in Fig. 6 that the experimental points calculated as described in the previous section can be divided into four regions according to pressure. These are: (i) below ~30 torr, (ii) between ~30 torr and ~300 torr, (iii) between ~300 torr and 1740 torr, and (iv) above 1740 torr. It has already been shown that because of the approximate nature of the treatment the theory will only apply in regions (iii) and (iv). Nevertheless it is difficult to understand the positive dependence in pressure exhibited in (ii) for even with a two-body electron attachment process operative

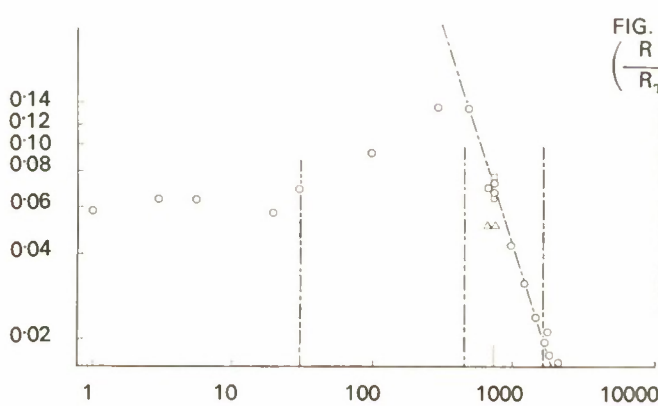

FIG. 6. Pressure dependence. Plot of function $\left(\frac{R}{R_T}-\frac{\eta V}{V_c}\right)\Big/\left(\frac{R}{R_T}-1\right)V^{\frac{1}{2}}$ in (volts)$^{-\frac{1}{2}}$ against Pill-Box dry air pressure in torr.
Vertical dotted lines demonstrate the division i four regions.
Points enclosed by squares were made at 3 m (upper) and 7 m (lower) distance between Pill-Box and accelerator.
Points enclosed by triangles were made using moist air.
Dotted line has slope representing pressure dependence of P.1.5.

the pressure dependence would be $P^{-0.5}$. In region (i) examination of the oscillograph records showed that near 5 torr during the charging phase the Pill-Box voltage rose steeply at the beginning of the pulse and considerably exceeded the equilibrium value to which it finally fell. It is probably significant that below this pressure it would be expected that each fast electron passing through the Pill-Box would produce an average less than one ion-pair or $\frac{dW/dx\ d}{\omega} < 1$ for $P<5$ torr. In region (iii) the points lie close to a line with a slope corresponding to a pressure dependence of $P^{-1.5}$ as predicted for the range of pressure where the theory holds and where electron conductivity is dominant. In region (iv) the departure of the points from this line is becoming apparent as the contribution of the ion conductivity becomes significant. The variation of pulse rate mentioned previously was not found to have any significant effect. Three measurements under identical conditions were made at atmospheric pressure and their average value of the expression on the L.H.S. of equation (35) is $7{\cdot}01 \times 10^{-2}$ volt$^{-\frac{1}{2}}$. If the ion conductivity can be neglected at atmospheric pressure then $\frac{dW/dx\ a}{\omega\beta} = 7{\cdot}70 \times 10^{-2}$ volt$^{-\frac{1}{2}}$ and using the previous value for $\frac{dW/dx}{\omega}, \frac{a}{\beta} = 10^{-3}$cm volt$^{-\frac{1}{2}}$. With $a = 3{\cdot}14 \times 10^{4}$ cm sec^{-1} volt$^{-\frac{1}{2}}$ from equation (34), $\beta = 3{\cdot}14 \times 10^{7}$ sec^{-1} which is more than three times smaller than the value predicted. It is unlikely that the quoted value of dW/dx is substantially incorrect. The source of the discrepancy is possibly in the energy of the secondary electrons produced by the ionisation process. These may not be thermalised completely before attachment and thus the probability of attachment will be different from that in a situation where electrons are released with low energy from a surface (qv electron attachment). The dependence on pressure of the drift velocity of the electrons is confirmed though it is possible that an adjustment of the multiplying constant $1{\cdot}23 \times 10^{6}$ is required.

Two measurements at distances between the Pill-Box and the accelerator of 3 m and 7 cm were made at atmospheric pressure and in the figure they can be seen to result in points greater and smaller in value respectively than the previous measurements. This is attributed to the effect on the second term on the R.H.S. of equation (35) of the variation in I and L consequent on the change in distance. At 3 m the value of I was reduced to 0·1 of its usual value because most of the current in the beam was intercepted by the impenetrable part of the Pill-Box front plate and L increased to become of the order of the recess radius, 12·7 cm. It should be noted, however, that this point is only some 10% greater than the average value at 50 cm. At 7 cm I is somewhat increased but it is difficult to predict the decrease in L.

Two measurements were also made at near atmospheric pressure with moist air. Fig. 6 shows that these produce values less than those at the same pressure in dry air. This is due to the increased attachment rate because of the high affinity of the water molecule for electrons. No attempt has been made at calculating the coefficient for water.

Fig. 3 demonstrates the linear relationship between Pill-Box voltage, corrected for the current in the measuring circuit, and plate separation. The "least squares" line goes nearly through the origin. This confirms the theoretical prediction of the absence of significant sheath effects.

The attempt to analyse the Pill-Box voltage decay curves previously mentioned was unsuccessful. Data could not be measured sufficiently accurately from the oscillograph traces to avoid the build up of very large errors during the computer operations of differentiation and reciprocation. It should be possible to overcome this difficulty by using smoothing techniques after each computer operation on the data.

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PROBABILITY, JUDGMENT AND MIND—EPILOGUE

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SUMMARY

The logistic curve has been applied previously to biological and population studies and to the description of certain growth curves observed in economic time-series. In four introductory articles the logistic is applied to problems arising in radar information theory, and, also, to experimental data from physics and quantum biology. A significant fact is pointed out early in these—that a transformation of the logistic leads to measures of subjective probability and hence to measures of information as in Shannon's information theory. The empirical use of the logistic is then supported by reference to the Bose-Einstein, Fermi-Dirac and Maxwell-Boltzman distributions; and current theories in particle physics and the concept of the Transfinite are introduced.

The papers, demonstrating the widespread applications of the logistic function, give way to the "Probability, Judgment and Mind" series and discussion, therein of mathematical models and subjective probability. Attention is drawn to the fact that subjective probability judgments inevitably involve the Unconscious in scientific inference. This leads to "suggestions" as to the nature, function and purpose of Mind: these are integral parts of the theory propounded by Dr. I. J. Good—the use of "suggestions" is to render the subjective scheme as objective as possible.

In this way consideration is given to the opinions of various authorities upon Mind and the Unconscious (Jung's Collective Unconscious in particular). Descriptions are interlaced with further relevancies of the logistic and its transformation.

Finally, a hierarchical set of equations is formed which represents the processes by which organisms of increasing complexity may adapt to their environment. The equations, taken with the latest theories in particle physics and other fields, appear to provide mathematical cum physical support for Jung's theory of Analytical Psychology taken as a whole.

A large work like "Probability, Judgment and Mind" requires a summing-up, and this final article discusses aspects such as afterthoughts, comments, etc., which, by their nature, can be dealt with only in an epilogue. Additionally, a summary is given of the complete series of articles, including those which feature applications of the logistic function.

I would like to stress that the articles are not intended to be read hurriedly or superficially; also that they suffer to some extent by being prepared in this form. In book form some material could have been relegated to notes at the end, and in those notes ideas could have been developed at greater length. As it was, to keep the work down to a presentable size many references were given

and only minimal descriptions—sufficient, however, to allow continued reading, with appropriate effort.

With regard to the content, since the articles were written, I have seen much to support my suggestions, but before expanding on this I feel that two points need further emphasis. Firstly, that the logistic bridges the gap between subjective probability and the natural approach to the study of physical and biological phenomena. Secondly, that the hierarchical set of equations developed, together with the physical and mathematical background, form an excellent foundation for C. G. Jung's theory of Analytical Psychology.

We may consider the two different definitions of Subjective Probability, (1) a school of thought about the logical basis of mathematical probability and (2) the transformation on the scale of mathematical probabilities which is somehow related to behaviour[1-4]—this series of articles unifies these two approaches. The need for fresh thinking on psychological models has been underlined by Professor J. Cohen in his recent book[5] from which the following quotation is taken: " There is scope for the development of a variety of models (or analogies) other than the reductionist sort which assumes, as a dogma, that only neuro-physiological models are acceptable in psychology ".

Next, to specify some of the extremely stimulating and pertinent items from recent scientific literature (these are numerous so only short descriptions are given—the relevancies will usually be evident).

(a) A suggestion by E. W. Fenton[6] is that macro-molecules, such as DNA, might be able to sustain superconducting currents of one type or another at room temperature. The postulated mechanism is compatible with the use of the logistic in particle physics and its transformation, giving measures of subjective probability and information theory.

(b) H. C. Dudley intimates[7] that physicists are beginning to describe an " aether-like " medium, namely the neutrino flux, consisting of a series of uncharged particles, of the order of $10^{11}/cm^2/sec$. With this series of particles, based on experimental data, a model has been developed which will provide many simplified, mechanistic explanations of certain physical phenomena, including the propagation of the electromagnetic radiation.

(c) S. J. Prokhovnik has re-introduced the aether concept and discussed time-dilatation [8].

(d) It has been suggested that speeds greater than the speed of light may occur for sound waves in a central " superluminal " core of a quasar[9].

(e) F. Hoyle and J. Narliker are convinced that some of the basic properties of atoms are linked to the large scale structure of the universe[10]. They have extended the theory of electrodynamics to discover its consequences in quantum physics, establishing a link between local electrodynamics and cosmology, and raising the possibility of testing different cosmologies by experiments on local systems.

(f) There is increasing experimental evidence on the effects of electrical, magnetic and gravitational fields on living systems[11, 12, 13] *et al.*

(g) The discovery of clouds of formaldehyde inside and outside our galaxy indicates that life may have begun in the depths of space and, also, that life may be widespread in the universe.

(h) Striking similarities exist to " Probability, Judgment and Mind " in the theme of " Robots, Men and Minds " by the well-known Ludwig von Bertalanffy[14]—see footnote.

(i) Poul Anderson[15] suggests that there is no selection pressure to increase intelligence above a level comparable to ours. Older races in the universe, by human standards, are likely to be emotional giants, with a balance, an insight, a creativity, such as we can hardly imagine.

(j) Increasing attention is being paid to representing the universe in terms of transfinite numbers[16, 17] *et al.*

(k) It is accepted that psychological time changes with age and this is not due only to changes in the " density of events "[18].

(l) An article in " Nature " stresses that the present-day view of Christianity is coloured by the time in history when Christianity arose[19].

To these could be added the suggestion that in group-testing for Telepathy it might be profitable to compose groups from those people who are most *susceptible* to hypnosis. This suggestion stems from our discussion on " psychons " and is prompted by the latest report in " Nature "[20] which seems to support the existence of extra-sensory perception. To actually have a subject under hypnosis would imply constraints imposed upon " psychons ".

Finally, to describe the comments I have received. I expected my reference to Freud and the Unconscious to provoke some correspondence. Perhaps it is a sign of the times that not one comment was received on this subject. I have been given much encouragement and support from colleagues and from former colleagues now scattered in many establishments. The one exception to this was a bitterly hostile letter from America (not sent directly to me) which was occasioned by the first article to touch upon Religion. Others have liked this article and I suspect that, as C. S. Lewis would have said, the nature of this letter indicates that a particular target has been hit!

FOOTNOTE

Ludwig von Bertalanffy is a distinguished biologist who has fought long and hard against wrongly-applied mechanistic thinking in the life sciences. He writes, as did Schroedinger, about the mysterious development of living systems towards decreased entropy and towards increasingly improbable states; with increasing differentiation and order.

The complexities of living organisms, especially the higher organisms, are such that in his opinion we need a conceptual approach radically different from classical physics. He believes that in general systems theory we have the beginnings of a new theoretical scheme, although he admits that perhaps some radically new mathematical discoveries will have to be made before this theory can be generalized to subsume all the complexities of living things.

In a scheme which may be accused of being metaphysical, vitalistic and anti-scientific, von Bertalanffy proposes that activity, and not re-activity, should be seen as the basic characteristic of living creatures and anticipates a new theory emerging from recent advances in molecular biology which will re-introduce teleology into the evolutionary process.

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THE CONTROL OF MICROBIOLOGICAL DETERIORATION IN MARINE SERVICE

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SUMMARY

The adaption of microorganisms for the efficient degradation of organic materials is described, and the mechanisms by which they can cause damage to materials and malfunctioning of equipment is considered. The fundamental principles underlying the protection of materials from attack are illustrated by references to specific problems met with in textiles, timber, paper, adhesives, plastics, hydrocarbons, paints and various items of equipment. The rationale of testing materials and equipment for their resistance to attack is outlined, and the need for continuing co-operation between designers, users and microbiologists is stressed in order to bring about maximum reliability and economic saving.

Introduction

The fundamental pattern of life on earth is a continuous sequence of synthesis and degradation. Plants grow in the soil, mature and die, or are eaten by animals which in turn die; their remains are then broken down by lower organisms, until finally they are transformed into fresh soil and the cycle is completed. The most powerful agents concerned in this degradation process are the microorganisms—microscopic creatures, strictly definable neither as plants nor animals, the most important groups of which are the fungi and the bacteria. Microorganisms perform their role in this process by actively eating the substances concerned. They secrete enzymes which split large, insoluble organic molecules into smaller, soluble units which can be absorbed through their cell walls and used as food. Thousands of specialised forms of fungi and bacteria have been evolved, each producing a limited number of enzymes capable of degrading only a few types of substance, and functioning at maximum efficiency over a restricted range of temperature, humidity, pH, etc. However, such has been the diversity and success of their adaption to this role, that appropriate organisms exist which can degrade virtually all natural organic substances under almost every environment occurring on earth. The reproductive powers of the fungi and bacteria are prodigious; under favourable conditions literally millions of fungal spores or new bacterial cells or spores, can be produced in a matter of days. This reproductive capacity is matched by highly efficient methods of disseminating their spores by air currents, water, soil or dust particles, etc. Wherever a potential food source exists in nature, it will rapidly become infected with, and eventually devoured by, an appropriate microorganism.

In view of the efficiency with which microbiological breakdown of organic matter occurs in nature, it is hardly surprising that the majority of materials of natural origin which are used by man should be susceptible to the same process. Hence timber, paper and other wood products, natural fibre textiles and cordage, animal and vegetable oils and fats, wool, leather, animal glues and starch or cellulose-based adhesives, natural rubber, mineral oils, etc., must be regarded as potentially degradable by microorganisms. Moreover, a wide range of synthetic materials, whose structure is sufficiently akin to natural materials to render them susceptible to microbial enzyme

systems, must also be considered at risk. Thus many synthetic components of plastics, paints, textiles, adhesives, etc., must be added to the list of vulnerable materials.

In addition to this direct attack on materials by microorganisms, of equal importance are the various forms of indirect damage which can result from their growth. During service many items of equipment will inevitably accumulate deposits of dust, grease, etc. on their surface, and moulds can produce significant growth on quite slight traces of this contamination. In some instances such growth can release metabolic waste products which may stain or corrode the underlying material, even though this may be completely resistant to direct enzymic attack. In other cases the physical presence of the mould growth may cause such defects as the shorting of electrical circuits, or even blockage of moving parts, clogging of filters, etc. Furthermore, under certain conditions mould or bacterial growth may initiate corrosion of metals by establishing conditions for electrochemical attack. Needless to say, mould growth on a susceptible material which is in contact with a resistant one may produce similar effects upon the resistant material.

It must be stressed that while the activity of microorganisms is most rapid at elevated temperatures and humidities, microbiological deterioration is by no means exclusively a tropical problem. Deterioration can occur, albeit more slowly, under many temperate environments. Nor must it be forgotten that "tropical climates" may easily be reproduced in temperate zones; a warm, damp store, or the interior of a submarine under closed-down conditions, may closely approach this environment.

Methods of Control

The rotting of such items as timber and textiles has been recognised as a microbiological phenomenon for nearly two centuries, and even before that time empirical methods of control were used. However, it was not until the 1941 - 45 war in the Far East that the ease and rapidity with which microorganisms can attack a wide range of manufactured materials were fully brought home to the armed services involved. Vast quantities—some estimates suggest millions of pounds worth—of military stores were rendered unserviceable often within weeks of entering service in a hot, moist tropical climate. Not only clothing, tentage, cordage, etc. suffered in this way, but also electrical and electronic equipment, optical apparatus and other types of military hardware previously considered to be immune. Urgent research programmes were initiated in the U.S.A., U.K. and Commonwealth countries to combat this menace, and although these efforts fell short of complete success, a basic fund of knowledge was obtained which has been steadily increased over the succeeding years.

It is now recognised that there are four fundamental lines of approach which may be considered when seeking to prevent microbiological attack on materials. Firstly, when faced with the problem of a material which is directly attacked by fungi or bacteria, the most satisfactory solution is almost always to replace the susceptible material with a completely, or comparatively, resistant one. Secondly, if for technical or economic reasons this approach is impracticable, a fungicide or bactericide may be incorporated in the material to render it more resistant to attack. Although these biocides can offer virtually indefinite protection in only a few cases, their use can in many instances render susceptible materials almost as efficient as resistant ones. A wide range of such substances is available, each with its particular advantages and disadvantages with regard to compatibility with materials, range of activity, cost, etc. Thirdly, the solution of a biodeterioration problem may sometimes be sought entirely through control of the environment, particularly bearing in mind that humidity is a limiting factor for mould growth. As a generalisation it can be assumed that significant attack will occur only if the relative humidity of the environment exceeds 70%, or if the moisture content of a material is in equilibrium with a humidity in excess of this figure. The application of environmental control measures has obvious limitations for items of equipment during actual use, but is often a valuable line of approach for the protection of packaged or stored items. Fourthly, it is sometimes possible to sterilise items of equipment and to protect them from subsequent contamination by airborne fungal and bacterial spores. Gaseous sterilisation techniques, or even radiation sterilisation methods are available for the treatment of suitable materials, and although the use of such methods is clearly limited, they may on occasion be considered for the protection of packaged materials.

A brief survey of some practical problems encountered in naval service may assist in the appreciation of the reasons for selecting particular control measures to combat various forms of microbial attack.

(a) *Textiles and cordage.* Natural fibre materials—*e.g.* flax canvas, cotton fabrics, and sisal or manila rope—may be readily attacked by cellulose-destroying microorganisms, and under severe conditions of exposure can be rendered unserviceable in a matter of weeks. A logical solution is to employ synthetic fibre materials instead,

and increased rot resistance was a considerable factor favouring the introduction of nylon and terylene fabrics, and nylon, polypropylene and terylene ropes into navy service. However, synthetic fibre ropes are not without their own particular problems, which include high stretch and elasticity, tendency to actinic degradation, poor abrasion resistance, etc., and moreover they are several times more expensive than are natural fibre ropes. The fungicidal treatment of sisal or manila with formulations containing copper-8-hydroxyquinolinolate can confer greatly increased rot resistance to ropes, and it is possible that for certain uses such material will prove more economical and technically superior to synthetics. Although without question the most effective fungicidal treatment known for natural fibre materials, copper-8-hydroxyquinolinolate is not without its disadvantages. For example, as its copper content catalyses the oxidation of rubber it cannot be used to protect fabrics which are to be proofed with rubber compounds. This prevents its use in rubber/cotton inflatable liferaft fabrics, which can suffer from mould decay in spite of protection with pentachlorophenyl laurate—a widely used and reasonably effective fungicide for textiles under moderate conditions of exposure.

(b) *Timber*. Although timber is not currently being used as a major component in ship construction, a number of wooden hulled craft, particularly mine sweepers, are still in service. When used for hull construction, timbers which show a fairly high natural resistance to decay (e.g. mahogany) frequently give many years of trouble-free operation provided normal protective painting standards are maintained. However, in cases where damage has allowed water to enter between the double layers of timber, attack by wood-destroying fungi can occur and cause extensive decay (see Fig. 1). In such cases the only remedy lies in careful surveying and complete removal and replacement of affected timbers. Numerous wooden components are still employed in the construction of certain craft, and in interior fittings of larger vessels. If less naturally resistant timbers are preferred for their superior physical properties, considerable protection can be afforded by impregnation with fungicides. In contrast with its efficiency on other cellulosic materials, copper-8-hydroxyquinolinolate here shows no marked superiority to several cheaper fungicides, such as pentachlorophenol or tributyltin oxide. It must always be remembered that in the protection of timbers, effective penetration is of prime importance and hence pressure impregnation of bulk timber is often to be recommended. Moreover, the type of fungicide and the particular formulation used must be compatible with subsequent user requirements, such as painting or other surface coating, contact with metal fixtures, etc.

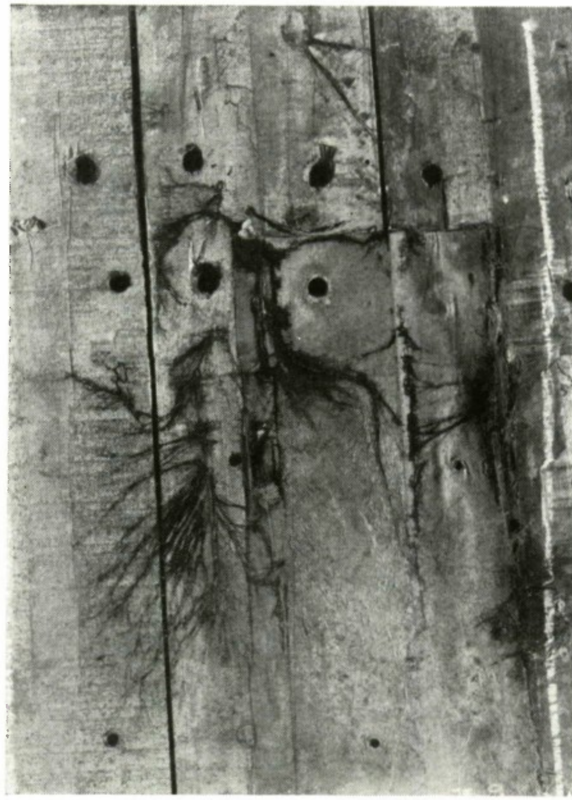

FIG. 1. Mahogany planking from hull of coastal minesweeper decayed by *Coniophora cerebella*

(c) *Paper and board products*. By nature extremely susceptible to microbiological damage, paper and related cellulosic woodpulp derivatives can nevertheless be given reasonable protection through the addition of a fungicide during manufacture. Many different toxics have been used successfully in these materials, and various waterproofing techniques also assist rot resistance. However, paper derivatives are seldom suitable for use under severe conditions of exposure, and more durable substances are obviously to be preferred for use in such environments. Nevertheless, for certain

usages, e.g. for many labels, paper has sufficient advantages in cost and convenience to render it worth while seeking improved protective measures. Overcoating with fungicidal and waterproof varnishes is used, but this interferes with the subsequent writing of amendments on the label. Excellent preservation of labels can frequently be obtained by incorporating a fungicide in the underlying adhesive, as described in the following section (d).

(d) *Adhesives.* Animal glues and starch or cellulose-containing adhesives are very prone to microbial attack. Many adhesives based on rubber formulations, synthetic resins, etc., on the other hand show excellent fungal and bacterial resistance. The selection of adhesives for most constructional purposes therefore presents few difficulties from this point of view. Where a more susceptible adhesive is more convenient and economical, however, the addition of a highly active fungicide can confer protection not only upon the adhesive but also upon the overlying material. Fig. 2 illustrates the effectiveness of a fungicide such as captan in protecting paper labels affixed with a P.V.A. based adhesive.

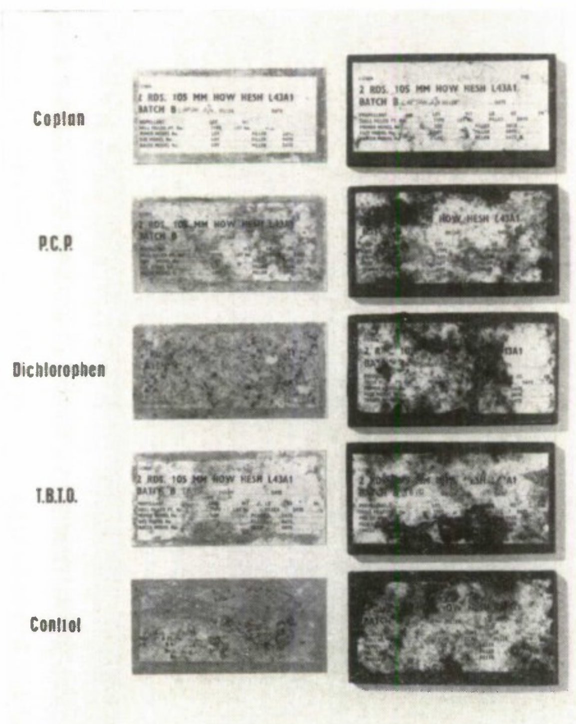

FIG. 2. Relative efficiency of fungicide- containing label adhesives as shown by exposure to four weeks soil burial test.

(e) *Plastics.* The majority of synthetic polymer molecules are immune to direct enzymic attack. Whether this resistance stems from an innate inability of micro-organisms to split the carbon chains, or from spatial effects impeding enzymic access to the molecules, is not clear. Whatever the reason, such materials as polyalkenes, polyamides, polystyrene, etc. in practice suffer no significant attack. Polyurethanes, on the other hand, exhibit differences in susceptibility, as might be expected from a class of compounds with such a variable structure. Our knowledge of the resistance of the numerous possible polyurethane formulations is far from complete, but, in general, polyethers are less susceptible than are polyester compounds. Other plasticised materials, such as P.V.C., also show differing degrees of resistance depending upon formulation. Here again, the P.V.C. molecule itself seems to be completely inert and the extent of attack depends on the nature of the plasticisers used; fatty acid esters such as sebacates and adipates are readily degraded, whilst phosphate and phthalate esters are less easily broken down. Such is the range of plastics materials available that, with the possible exception of polyurethanes, there is likely to be no large-scale requirement for the addition of fungicides to these materials. Where these are required, various organotin compounds and chlorinated phenols have provided reasonable immunity. In a different category, however, are composite materials such as textile/polymer laminates or polymeric materials containing cellulosic fillers. Here, protection of the degradable component with a compatible fungicide may be essential. Finally, it may be mentioned that many instances of supposed mould growth on plastics have, in fact, proved to be due to the fungus developing on superficial deposits of extraneous organic matter (see Fig. 3). In other instances, growth has been known to occur on traces of release agent or other surface additives to plastics. While such superficial mould may be no more than aesthetically unpleasant, in common with attack on plasticisers, it may produce significant changes in physical properties of the material and should never be disregarded as unimportant until its effects have been fully investigated.

(f) *Hydrocarbons.* Although popularly regarded as biologically inert materials, hydrocarbons —fuels, lubricating oils and hydraulic fluids —can be degraded by certain micro-

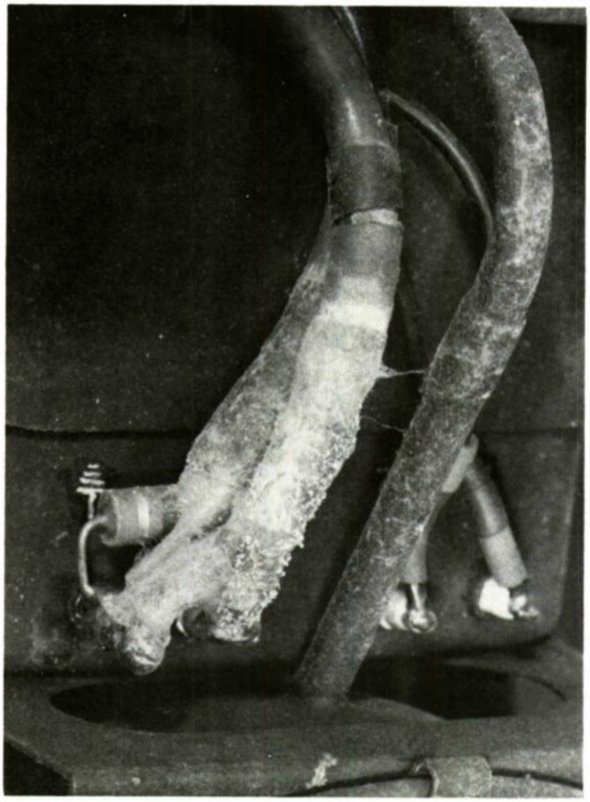

FIG. 3. Mould growth on P.V.C. cable insulation of radio equipment.

organisms in the presence of free water. In such cases, any adverse effect on the hydrocarbon itself is usually negligible, although the utilisation of additives by fungi and bacteria may occur in some instances. The serious aspect of such attack lies in the ability of micro-organisms, and particularly the fungus *Cladosporium resinae*, to produce extensive masses of growth which can block valves and filters and cause failures in capacitance gauges, etc. Moreover, it has now been demonstrated that this fungus and possibly other organisms, when lying in contact with metal structures such as an aircraft integral fuel tank, can establish a corrosion cell probably of the oxygen concentration type. Considerable reduction in the severity of such growth in fuel and oil systems can be achieved by " good housekeeping " practices and attention to design detail in order to minimise the amount of free water which can enter the system, and to allow for its easy removal. However, the complete eradication of water from such systems is often difficult or impossible and alternative measures must be sought. Where a well-defined water phase can be located, the addition of water soluble biocidal materials such as chromates may be successful. Where free water is more diffuse, an oil/water soluble biocide may be necessary; such materials are added to the hydrocarbon phase and by virtue of a high partition coefficient with respect to water will build-up toxic concentrations in the aqueous phase. A proprietary mixture of organoborinanes is the most successful material of this type so far generally available, and it has found use in hydraulic rigs and to a limited extent in aircraft fuels. Its use in aircraft, however, is impeded by the reluctance of aero engine manufacturers to permit the burning of organoboron compounds in their turbines. Even as an occasional sterilisation treatment it nevertheless shows remarkable promise.

(g) *Paints*. Many emulsion paints and oil based paints contain sufficient nutrient to support mould growth. Those which are constitutionally inert, such as chlorinated rubber paints, may also develop growth on their surface through an inevitable accumulation of dust, etc. Hence, particularly in situations where condensation can occur, painted surfaces are frequently disfigured, and eventually damaged, by microbial attack. Fortunately, several fungicides exist which will give excellent protection, and organomercurials, organotin compounds, and captan and certain of its analogues all find their use in paints, and impart resistance to both direct attack and superficial growth.

(h) *Equipment*. It is now rare to find an extremely non-resistant material incorporated into mechanical, electrical or optical equipment or weapons. More common are design defects which permit unavoidable superficial growth to interfere with the proper functioning of the equipment. Attention at the design stage to such details as encapsulation of possibly sensitive components, judicious siting of exposed electrical contacts and delicate moving parts, the provision of localised heating coils to prevent moisture and mould affecting susceptible areas, can all save considerable time and expensive modifications during service. The use of fungicidal varnishes and paints is sometimes beneficial, and proper packaging and storage is of course essential. Nevertheless, wherever equipment is to be used in severe environments there is no more effective control measure than to ensure that it can function in the presence of superficial fungus growth.

Evaluation of Control Measures

Finally, some consideration must be given to the techniques which enable a comparison to be made between various alternative methods of controlling microbiological deterioration of materials and equipment. The behaviour of a material when exposed to various microbiological effects cannot often be accurately predicted from a theoretical knowledge of its structure. With an ever increasing range of novel materials being considered for use in naval service, this implies a need for continuous screening of such products for their resistance to various forms of attack. Similarly, it is impossible to predict the precise activity which a given biocide will exert when used in any particular material, and a detailed study of such activity is required for each separate context. Moreover, the effect of biocides on the physical and chemical properties of materials, their resistance to actinic degradation, and frequently their human toxicity, must also be considered.

The main problem pervading all testing of resistance to microbiological damage lies in the impossibility of accelerating such tests without imposing conditions so far outside the natural environment as to cast doubt upon their validity. Although this situation to some extent affects all environmenal testing, it is a particularly difficult one in this field, for although microbial growth can occur at considerably elevated temperatures, the organisms which will operate under such conditions are not necessarily those which will cause maximum damage. In short, the maximum acceleration of testing which can be accepted involves the exposure of materials to the most active organisms under moist, tropical conditions, *i.e.* at temperatures of 30 - 35°C and humidities in excess of 95% R.H.

Thus for many purposes a short-term trial is of necessity employed, and inferences drawn as to the probable long-term performance of the material or protective treatment under study. A typical example of such practice is to be found in the testing of components and equipment by climatic chamber trials such as those included in the environmental test specifications DEF-133, DEF-5011, DTD-1085 and BS-2011 in the U.K., and MIL-STD-810B and MIL-E-5272 in the U.S.A. One general exception to this maxim of "simulated tropical exposure" testing is where certain products, particularly textiles, are exposed to artificial and somewhat arbitrary test conditions such as soil burial, or to specific organisms in pure culture tests. Such techniques have by experience been found to give reliable indications of the relative merits of different fungicidal treatments.

Nevertheless, success in even the most efficient laboratory trial may not be a guarantee of failure-free service during prolonged exposure to severe environments, when unexpected problems may arise through the effects of persistent microbiological activity. Although the factors of time and expense only too often militate against it, actual long-term tropical field exposure trials are sometimes the only satisfactory way of achieving unequivocal results. For this reason the facilities offered by such exposure sites as the Joint Tropical Research Unit in Australia, and the U.S. Army Test Centre in Panama are extremely valuable.

In spite of all our best efforts during the design and development stage, it is of course inevitable that some microbiological problems will occur during service. Although in most instances the nature of the defect will be immediately apparent, sometimes the true cause will be less easy to detect. It is therefore important that service personnel and inspectorate staff bear in mind the possibility that microorganisms may be responsible for damage without betraying obvious signs of their presence, and that such cases be reported to the appropriate organisation for investigation.

Conclusions

There are surprisingly few materials used by the armed services which are completely immune to every possible form of microbiological deterioration. It is impossible accurately to assess the economic cost of a deterioration process which insidiously affects such a wide range of materials and equipment. It has recently been conservatively estimated that the face value of industrial materials which are destroyed annually in Western European and North American countries exceeds $1,000 million. When one adds to this figure the vastly greater costs incurred in replacement labour, loss of operation, and other related disruption which may result through failure, the true costs are seen to be tremendous.

Considerable advances have been made in understanding and combating this problem, and currently this is an active area of research in many countries. Further studies into the principles of microbiological attack and of fungicidal protection and materials resistance will undoubtedly lead to further progress. Nevertheless, without full co-operation from design authorities and the user departments, the efforts of microbiologists to minimise the effects of microbiological deterioration will be less than fully effective. Most service departments of the U.S. and Commonwealth countries have access to efficient research facilities in this field, and the maintenance of close liaison between them can bring considerable benefits of increased operational efficiency and economic savings.

REPORT ON THE 1969 I.E.E.E. EUROPEAN MEETING ON SEMICONDUCTOR DEVICE RESEARCH

Reported by L. N. Large
Services Electronics Research Laboratory

The 1969 I.E.E.E. European Meeting on Semiconductor Device Research was held in Munich, Germany, between March 24th and 27th. Each day commenced with two one-hour invited papers and there followed contributed papers of 20 minute duration in two parallel sessions. It is proposed to publish only the invited papers in " Festkörperprobleme " at a later date.

The proceedings opened with invited papers by G. A. Acket and T. Vlaardingerbroek on " Physical Investigations of New Microwave Devices " and by M. Zerbst on " New Results in M.I.S. Transistors ". The former was an up-to-date summary of the position on IMPATT'S and Gunn devices with predictions as to the future performance of these and associated types of devices. Dr. Zerbst concentrated mainly on the role of new insulators, such as alumina, in field-effect transistors. In the sessions that followed there were papers on field-effect transistors and special bulk effects. Of particular interest were two papers describing field-effect transistors capable of operating at microwave frequencies. These described silicon devices with 1μm channel widths, obtained by using microprojection techniques. In addition there were contributions describing the observation of microwave oscillations in bulk silicon and germanium and avalanche processes in indium antimonide.

Tuesday began with invited papers by R. S. Engelbrecht on novel device concepts using bulk negative resistances and by L. N. Large and K. G. Hambleton on the application of ion implantation to semiconductor devices. Both these reviews described work which may have a significant influence on the semi-conductor device field of the future. A session on light generation included papers on the theory of laser action in field-ionised bulk semiconductors, on the use of zinc telluride for electroluminescent diodes and the degradation of the electroluminescent efficiency of gallium phosphide diodes under forward biased operation, which the author claimed was mainly due to copper impurities in the lattice migrating to the junction. There were also papers on technologies such as solid-solid diffusion, liquid epitaxy and a novel method for making thin layer devices. There were some eight papers given consecutively on Gunn and L.S.A. devices including the latest techniques for fabricating them to achieve high c.w. powers and the description of a computer analysis of L.S.A. operation in thin layers of GaAs.

The session on opto and acousto-electronic devices included interesting papers on the simultaneous observation of microwave emission and acousto-electric excitation in n-type InSb and methods for manufacturing solar cells capable of operation at high temperatures.

The invited papers on Wednesday were by H. K. Gummel on computer device modelling and by O. G. Folberth on monolithic memories. Perhaps one of the most important features of this conference was the growing use of the computer for device modelling leading to optimum designs, prediction of performance and a greater understanding of the mechanisms involved. There followed a session on memories and on galvanometric devices. On Wednesday afternoon there was a session on avalanche transit time diodes in which the rapid development of this field was reflected by some excellent papers. A development promising to be very important in the future was the reported use of IMPATT devices as amplifiers rather than oscillators.

On the final day invited papers were given by W. Gerlach and G. Kohl on high voltage thyristors and by H. Ullrich on modern methods for making masks for semiconductor devices and circuits. The former paper presented a survey of existing problems concerned with attaining high voltage devices and cooling them and described new structures for improved performance. The latter reviewed the developments in mask making and highlighted the future use of the computer in this field. There followed contributed papers on thyristor development and on bipolar transistors including prospects for germanium devices for low noise amplification and new techniques for passivating and masking germanium devices. Finally, there were contributed papers on computer-aided design, showing the very close agreement between predictions made by the computer and observed experimental performances and new technologies such as holographic storage for integrated circuit masks.

In conclusion, this meeting included papers on a wide variety of semiconductor devices and associated techniques, comprising a valuable collection of information. Presentation was, in general, of a high standard and lively discussion periods reflected the interest of those attending.

Books available for Review

Offers to review should be addressed to the Editor

The Design of Design.
G. L. Clegg.
Cambridge University Press. 1969. 30/- (No. 1743)

Advanced Level Applied Mathematics.
C. G. Lambe.
The English Universities Press. 1969. 28/-. (No. 1744)

The Physical Basis of Metal Fatigue.
P. J. E. Forsyth.
Blackie and Son Ltd. 1969. 60/-. (No. 1745)

Defects and Radiation Damage in Metals.
M. W. Thompson.
Cambridge University Press. 1969. 120/-. (No. 1746)

Fundamentals of Operations Research.
R. L. Ackoff and M. W. Sasieni.
John Wiley and Sons. 1969. 97/-. (No. 1747)

Operations Management.
E. S. Buffa.
John Wiley and Sons. 1969. 100/-. (No. 1748)

The Space Environment.
Edited by N H. Langton.
University of London Press. 1969. 35/- (No. 1749)

Transmission Lines and Waveguides.
L. V. Blake.
John Wiley and Sons. 1969. 88/-. (No. 1751).

ONE APPROACH TO THE BARNACLE PROBLEM

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Exposure Trials Station
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A fouling community may consist of a few or many different kinds of living organisms varying in size, shape and colour. Those likely to be found on ships include bacteria, fungi, algae, small plant-like animals known as polyzoans and hydroids, sea squirts, serpulid worms, mussels and barnacles. The latter are the most universally important, there are nearly six hundred species but not all are found in fouling communities. They live in every form of habitat within the marine environment from the deep seas to exposed rocky shores. A few species live on whales and others are degenerate parasites which are difficult to identify as cirripedcs. Barnacles are extremely resistant to unfavourable conditions, being able to withstand days of exposure, lack of food, a wide range of temperatures and salinities.

The economic importance of barnacles, as fouling agents is considerable. It has been estimated that thcy cost the United States Navy some 280,000,000 dollars per year and it has been calculated that the increase in fuel consumption due to increased drag arising from marine fouling as a whole amounts to some 40%.

Marine biologists have devoted considerable effort to the study of the barnacle and its habits. These studies include taxonomy, morphology and anatomy, physiology, ecology and behaviour. The aim of this article is to show how work in these fields may ultimately help in the control of marine fouling, both by improvement of present techniques and the development of new ones.

It was not until 1830 that barnacles were recognised as being related to crabs and lobsters: previously it was generally thought that they were molluscs. However, Vaughan Thompson a keen amateur marine biologist found that the early larval stages in the life history, known as nauplii, were free living in the plankton and most significant of all that they were typical Crustaceans.

There are six naupliar stages, the first hatching out of the fertilised eggs which are retained in the mantle cavity of the adult. Each stage becomes progressively larger and more complex than the next. The adult barnacle is a sedentary animal and the nauplius represents the dispersal phase in the life history. It possesses swimming appendages which are the first and second pairs of antennae and the mandibles; there are no legs present in the nauplius. The animal has mouth parts and a gut and feeds on microscopic plants known as diatoms which are found in the plankton. The sixth stage nauplius changes into a larva which externally appears very different in shape and form. This larva is known as a cypris and is specially adapted for substrate selection. The first pairs of antennae are highly specialised organs with an attachment disc at the end which links up with the cement glands by means of a duct running throughout the length of the antenna. The mouthparts are much reduced and sections of the animal reveal that the anterior and posterior lumens of the gut are closed, it is therefore not able to feed. There are vacuoles filled with oil which serve as a food reserve and probably are a device which helps reduce the specific gravity, thus helping the cypris to achieve neutral buoyancy.

Cyprids have two kinds of locomotion, the antennae are used for 'walking' over the surface of the substrate and are presumably equipped wth

sensory devices enabling the animal to test the character of the surface. The six pairs of thoracic appendages which are first visible externally in a reduced form by the time the sixth stage nauplius is reached, serve as the propulsive organs of the cypris.

Behavioural studies at the time of settlement have shown that this process is not a random or passive affair and that many factors determine whether settlement will occur in a particular area or not. One of the most important is gregariousness. Barnacles live together, often in overcrowded conditions. A solitary barnacle would be unable to take part in reproduction, since in spite of the fact that barnacles are hermaphrodite, cross fertilisation is the usual rule. It has been shown that cyprids are attracted to the bases of old barnacles which remain attached to the substrate after the adult has been lost. This attraction is a chemical one. Apart from its importance in perpetuation of the species, this mechanism has survival value since it ensures that cyprids will settle in situations which have previously proven suitable for barnacle attachment. The nature of the substrate is also important. Although cyprids will apparently settle on any type of surface both living or inanimate there is a distinct preference for rough rather than smooth surfaces, settlement usually being heaviest in grooves and depressions. Some of the most interesting observations on cypris attachment are concerned with the colour of the substrate. During daylight more settlement occurs on dark coloured substrates than light coloured ones (Visscher 1928). At night, however, settlement appears to be about the same on both types. In an experiment (Phelps 1942) aimed at distinguishing between the effects of gravity and light some painted and glass panels were positioned horizontally beneath a barge. Observations showed that there was more light beneath the panels than on top. More barnacles were found on top of the painted panels whereas there were equal numbers on the top and bottoms of the glass ones. This result indicates that when the effects of light and gravity were opposed, the cyprids react primarily to light. When the clear glass panels were hung beneath the barge at night, more cyprids settled on the underside. When light was at a minimum therefore, the cyprids reacted to gravity.

After attachment to the substrate by means of the cement, metamorphosis occurs and the adult structure is attained. The adult barnacle is enclosed within a shell consisting usually of four or six plates.

Once the adult stage has been attained and the barnacle well established toxic compounds are of little use for although the young adult is less resistant to copper than the cypris and the toxic constituents may kill the animal, the shell remains producing an increase in frictional resistance. An antifouling agent therefore, should aim at attacking the cypris stage preferably before it settles. Present antifouling paints incorporate copper compounds which leach out into the water. It is not known how these effect the metabolism of the animal but they are thought to interfere with the enzymes involved in the respiratory process.

One of the most fundamental questions concerning barnacle development remains to be answered, this is what controls the change from nauplius to cypris stage and cypris to adult. In other words what factor or factors control metamorphosis? The changes which occur in structure during development are gradual and are related to the needs of the particular stage in the life history; for example, the thoracic appendages and their musculature which are not used until the cypris stage, do not develop as separate entities until the late naupliar stage. Structures necessary to the nauplius are lost by the time the cypris is reached, the second antennae of the nauplius are not used by the cypris for swimming so these are lost. At some point, then, in the life history, one or more factors are responsible for "triggering off" the genes which determine the development of a particular structure. If we could determine what these factors are, it is feasible that biochemical blocking agents could be employed which would prevent development. Whether such agents could be incorporated in anti-fouling paints, is of course, a problem for the paint technologist.

Research being carried out at the Exposure Trials Station, is aimed at answering some of these questions. It has been known for some time that metamorphosis in Insects and colour change and moulting in some of the Crustaceans are controlled by chemical substances known as hormones. These substances are released into the blood and eventually reach their "target organs" where they "switch on" the genes which bring about the change. Hormones are present in most groups of animals, insulin produced by the pancreas of man is a well known example. The hormones which concern us here, however, are included in a special category because they are not produced by glands but by actual nerves or neurons, and are called "neurosecretions". Only a small proportion of neurons in the animals studied are found to be neurosecretory, the rest are concerned with the transmission of the nerve impulses. In this respect neurons fall into three categories — sensory neurons which receive a stimulus from a sensory area, and motor neurons which direct a particular muscle to respond. The

third type is neither sensory or purely effector-innervating but links neuron with neuron. The nervous system of an animal then, is a highly complex communication system by which the animal responds to both its external and internal environment. A typical neuron consists of a nucleus which contains the genetic material and surrounding this the cell body or cytoplasm. The latter is drawn out into thin fibres called axons and dendrites depending on whether the nerve impulse is travelling towards or away from the cell body. A collection of nerve cells in its simplest form is known as a ganglion, in such a collection the axons and dendrites form a tangled mass known as the neuropile.

Neurosecretory cells differ from ordinary neurons by having within their cytoplasm visible droplets of secretion. Such droplets can be seen under the light microscope after the cells have been fixed, sliced into sections a few microns thick and stained with special stains. Two of the most common are paraldehyde fuchsin (PF) and chrome—haematoxylin. After the droplets of secretion have been produced they are transported down the axon to a site where they are either liberated into the circulatory system or stored prior to release, in a neurohaemal organ. The sinus glands of the higher Crustacea is a good example.

Investigations have been carried out on nauplii and cyprids to determine if such a neurosecretory system exists in these larvae.

The work presents a considerable challenge since little is known about neurosecretory systems in lower Crustacea and also involves various technical difficulties. First it is necessary to have a ready supply of larvae throughout the year. In nature, they are available in the plankton only during Spring and Summer, also the number of cyprids collected from a plankton haul is usually small. A rearing technique has been developed in this laboratory to get over these difficulties. The task of carrying cut histology (the preparation of tissue for microscopic investigation and its subsequent examination), with such tiny animals present considerable difficulties. It is usual to cut sections in a definite plane, either transversely, horizontally, or longitudinally. Because of the size of the larvae, orientation inside the molten wax has to be carried out under the microscope. The correct alignment has to be achieved in the short interval before the wax solidifies. The skin of the nauplius and cypris is formed from a hard substance called chitin; this presented a further difficulty necessitating the use of a wax which will ribbon at 75°F. However, the small size of the animal which proved to be a disadvantage at light microscope level proved to be an advantage in electron microscopy. The high magnifications involved make one of the greatest problems that of locating the particular area in which one is interested; the smaller the mass of tissue worked with, the easier this proves to be.

Before a neurosecretory mechanism can be shown to be present in barnacle larvae certain criteria have to be fulfilled. These are as follows; where is the secretion produced, how is it transported, stored, released into the circulation, and finally what factors in the external and internal environments control the production of the secretion in the first place ?

Certain facts provide clues that a neurosecretory mechanism should be present in larval barnacles. It has been found that neurosecretory cells are present in the supra and infra oesophageal ganglia of adult barnacles (Barnes and Gonor 1958) and it is thought that these may control the breeding activity of the adult barnacle (Tighe-Ford 1967). As such cells are present in the adult one might reasonably expect them to be present in the larvae although there is considerable reorganisation of the nervous system during the final metamorphosis from cypris to adult with complete breakdown of some neurons.

Observations in the laboratory have shown that metamorphosis into the adult only occurs when the cypris larva has settled and become attached to the substrate. This would indicate that the actual process of settlement, or the various stimuli received by the nervous system from receptors in the antennae, may, by some means, trigger off the final changes leading to the formation of the adult structure.

Many sections of both nauplii and cypris nervous system have been examined for the presence of neurosecretory cells.

The nervous system of stages I - V nauplii consists basically of a relatively large ganglionic mass, the " brain " connected by the circumoesphageal connectives to a chain consisting of two pairs of ganglia. The anterior part of the brain receives nerves from the naupliar eye and frontal filaments. These two structures are of particular interest and will be described in more detail later. The posterior part of the brain gives off nerves to the antennules. The first pair of post oral ganglia are known as the antennal ganglia and the most posterior pair as the mandibular ganglia. By the time the Stage VI nauplius is reached a relatively larger pair of posterior ganglia are observed, these are the thoracic ganglia innervating the thoracic appendages. In reaching the cypris state the structure of the nervous system has undergone a change because of the development and loss of certain structures (Doochin 1951). The " brain " receives nerves from the nauplian eye and gives

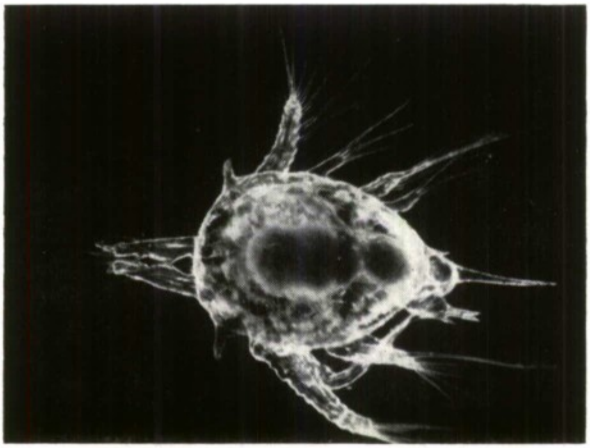


Plate I. Nauplius Larva of *Balanus balanoides* x 193

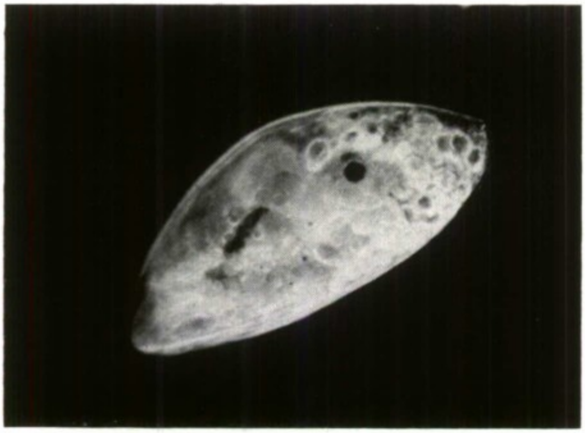


Plate II. Cypris Larva of *Elminius modestus* x 125.

Plate III. Adult Barnacles:
A *Balanus improvisus* surrounded by *Elminius modestus* ≃ x 5

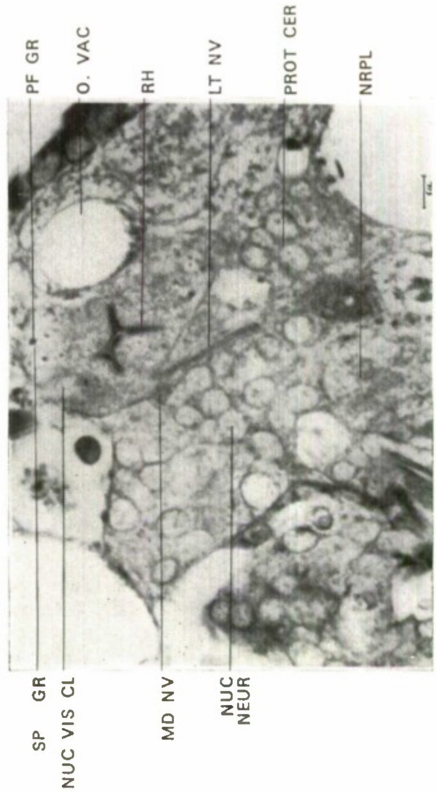


Plate V. L.S. of Median (Naupliar) Eye of Cypris of *E. modestus*

Plate IV. H.S. of Median (Naupliar) Eye of Stage VI. Nauplius of *E. modestus*

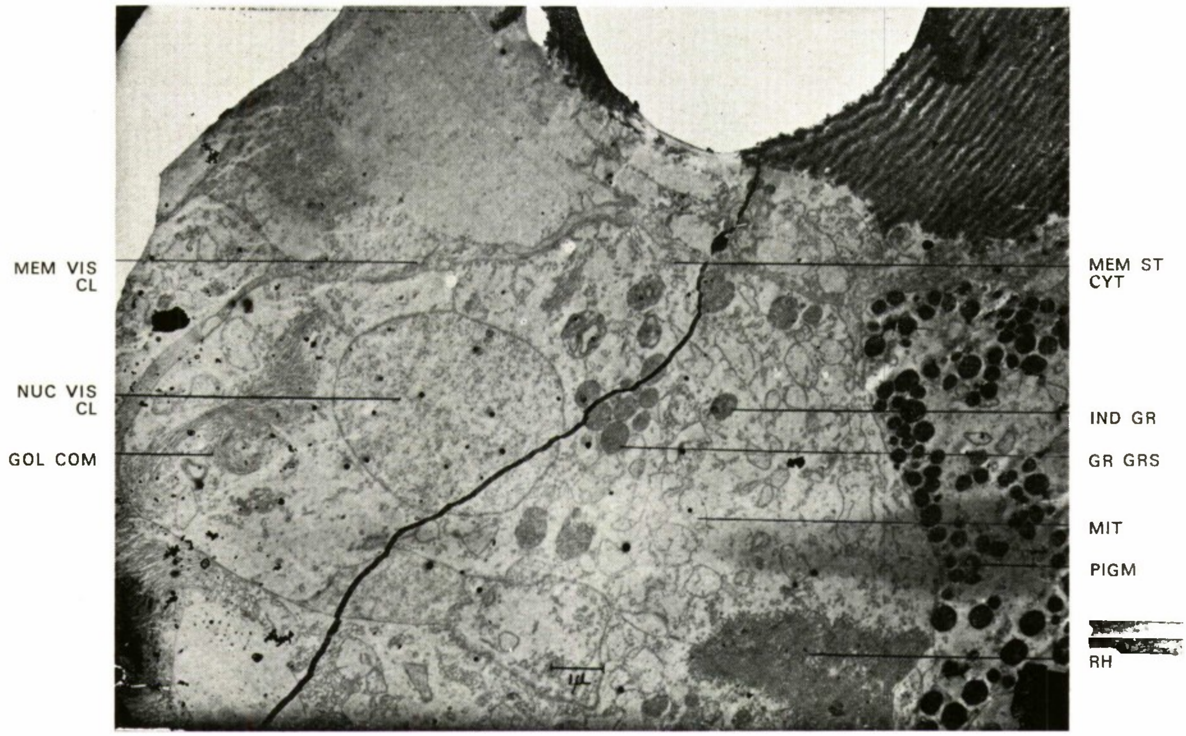


Plate VI. Electronmicrograph of L.S. Median (Naupliar) Eye of Cypris of *B. balanoides*

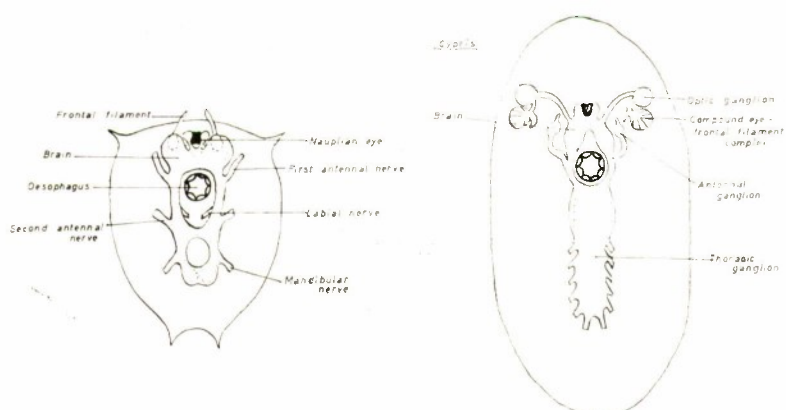
off nerves to the antennae which enter the antennal ganglia. Two optic ganglia are each situated in front of a complex formed by the compound eye and frontal filament. The thoracic ganglia innervate the thoracic Appendages (Fig. 1).

exhibiting the phenomenon known as positive phototaxis, i.e. they will swim towards a bright light source. Because of the importance of light special attention has been paid to the photoreceptors and these have proved to be very interest-

FIG. 1

Diagrams of Nervous System

Stage I - V nauplius.



Light is one of the major extrinsic factors effecting neuroendocrine systems; it has been shown that physiological processes such as moulting in insects can be altered by experimentally controlling the length and intensity of illumination to which the animals are subjected. Nauplii and cyprids are very responsive to light,

ing: barnacles have two types, the nauplian or median eye and the paired compound eyes. The compound eyes resemble those of insects; their development is complete by the VI stage nauplius, they are present throughout the cypris stage and are lost during the final change into the adult. The compound eyes then, are only of

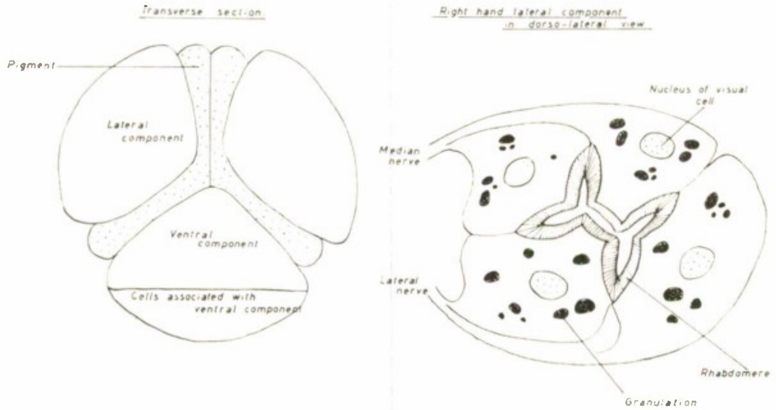


FIG. 2

Diagrams of the Nauplian Eye

(After Kauri).

functional importance to the cypris and as this stage is concerned with substrate selection they presumably play a part in this process. As already pointed out, cyprids prefer dark coloured substrates and can respond to different colours. It is proposed to carry out experiments to determine how both nauplii and cyprids respond to light of different wave lengths. Present evidence suggests that cyprid larvae exhibit greater activity in green light than in other portions of the spectrum (Walton Smith 1948). The nauplian eye, is present in all the naupliar stages, the cypris stage and in a modified form in the adult. The positive phototaxis exhibited by nauplii probably has survival value in keeping the larvae in the upper layers of the sea where the plants on which they feed, are found. It is possible, however, that the nauplian eye serves an additional function in the physiology of the animal, it may be the receptor by which light, acting through nervous pathways, controls an endocrine process. In this respect it is of interest to note that there is a link up between the modified nauplian eye and neurosecretory cells in the adult. In the adult stage the nauplian eye has become divided to form three photoreceptors, these are linked by nervous pathways to the supra oesophageal ganglia in which are found neurosecretory cells. Droplets of neurosecretion are also found in the nervous pathways linking the photoreceptors to the ganglia. If a shadow is thrown across a barnacle, the "legs" are withdrawn into the shell and the plates close up. The photoreceptors are concerned in "the shadow response". As breeding is affected by the length of daylight, in addition to other factors, the photoreceptors of the adult clearly play a more important part in the physiology of the animal than just shadow responses.

The nauplian eye of *Balanus* has been described by Kauri (1962). It consists (Fig. 2) of three pigment cups formed from two pigment cells. Each pigment cup supports one visual component, two lateral and one ventral. A group of two cells is found in association with the ventral component. There is an increase in size in the diameter of the eye as the cypris stage is approached. The naupliar eye gives off five nerves. There is one median and one lateral nerve from each lateral

KEYS TO FIGURES

ART	possible artifact.
AX	nerve axon.
CH	chromatin.
CL EL D GRS	cluster of electron dense granules.
CPT CYP	cuticle cypris.
CUT NAUP	cuticle nauplius.
DB MEM	double membrane surrounding granules.
EL D GRS	electron dense granules.
FIN PR	finger-like processes.
GOL COM	golgi complex.
GR GRS	group of granules.
INC	inclusion.
INC FIN PR	inclusion passing along finger-like process.
IND GR	individual granule.
KF MK	knife mark.
LAT COMP	lateral component of eye.
LT NV	lateral nerve.
MD NV	median nerve.
MEM ST CYT	membranous structures within cytoplasm of visual cell.
MEM VIS CL	membrane of visual cell.
MIT	mitochondria.
WRPL	neuropilem.
NUC NEUR	nucleus of neuron.
NUC VIS CL	nucleus of visual cell.
OL VAC	oil vacuole.
PF GR	PF granules.
PIG	pigment.
POS PIGM	position of pigment, removed due to oxidation prior to PF staining.
POSS NV END	possible nerve ending.
PROT CER	protocerebrum of brain.
RH	rhabdome.
SP EL D GRS	space surrounding electron dense granules.
SP GR	space surrounding granule.
SP GR AB BK DN	spherical granule about to break down.
SP GR BK DN	spherical granule which has broken down.

cup and a single nerve from the ventral cup. The nerves connect to a three lobed centre of dense neuropilem situated dorso-frontally in the protocerebrum.

The visual cells, also known as retinular cells, are sensory neurons. They resemble superficially the neurons in the brain; this is mainly due to similarity in the structure of the nuclei. There are, however, several important differences between the visual cells and the neurons. Part of the cell membrane of each visual cell is modified to form a complex structure, the rhabdomere. The rhabdomeres of each visual cell contribute to the formation of a rhabdome. The latter is concerned with the process of photoreception. The nuclei of the visual cells are larger in dimensions relative to those of neurons in the brain. The following example selected at random illustrates this point.

Visual Cell Nucleus		Neuron (protocerebrum) nucleus	
Length μ	Width μ	Length μ	Width μ
9·0	8·0	5·0	5·0
8·0	6·0	7·5	5·5
6·0	5·5	6·5	5·0
8·0	6·0	6·5	4·5
6·0	5·0	6·5	3·5
–	–	5·0	3·5

There is considerably more cytoplasm surrounding the nucleus of the visual cells relative to the cytoplasm of the neurons in the brain.

Kauri (1962) described granulations within the cytoplasm of the visual cells. The present study has shown that these granulations stain particularly well with paraldehyde fuchsin.

The granulations vary considerably in size (see Table I and II), the larger staining denser than the smaller. The rhabdome also stains purple with paraldehyde fuchsin and there is evidence (see plate V) that the nerves leaving the nauplian eye also take up the stain. Clearly there is a functional link between the rhabdome, granulations, nerves and brain. Since Kauri did not advance a hypothesis as to the function of the granulations, it was decided to use electron-microscopy to investigate their structure.

Two species of barnacles have been used in these investigations, these are the winter breeding *Balanus balanoides* and the summer breeding *Elminius modestus*. The electronmicrographs of the eye region of *B. balanoides* appear to be very different to those of *E. modestus* and it is thought that this variation is probably due to differences in fixation techniques. The function of a fixative is to preserve the tissues in a state as close to life as possible. *B. balanoides* larvae were subjected to a double fixation procedure being fixed firstly in 5% glutaraldehyde for two hours at 0°C and after washing overnight in a phosphate buffer, to osmic fixation for at least two hours. The *E. modestus* larvae were fixed in 1% osmium tetroxide only. At electronmicroscope level the granulations in the visual cells of *B. balanoides* larvae were seen to be roughly spherical granules situated mainly in groups comprised of a number of units but also occurring occasionally as single entities within the cytoplasm of the visual cells. Measurements were carried out on electronmicrographs to see whether the spherical granules could be equated with PF stained granulations at light microscope level. As no light microscope measurements of PF granules of *B. balanoides* were available, a comparison was made between the electronmicrograph measurements of *B. balanoides* and the light microscope measurements of *E. modestus* (Tables I and II). It was found that when treated as single units their dimensions were too small. If, however they were treated in groups with an imaginery circle or ellipse drawn round each group, the resulting structure had dimensions which did approximate to the light microscope granulations. It is suggested therefore that groups of these spherical granules correspond to the granulations at light microscope level. No other structures have yet been found in the cytoplasm of the visual cell of this species which could be equated to the PF stained granulations.

Electron Micrograph Dimensions of: Granule		*Space surrounding Granules*		*Light microscope measurement of P.F. Mass*	
Length μ	*Width μ*	*Length μ*	*Width μ*	*Length μ*	*Width μ*
1·84	1·02	3·07	2·25	3·0	2·5
1·53	0·41	2·66	1·23	2·5	2·5
1·84	0·72	2·97	1·84	1·0	1·0
0·46	0·65	3·34	2·19	1·5	1·5
0·83	0·26			3·0	2·5
				2·0	1·0
				1·5	1·0
				0·5	0·5
				2·0	1·5
				2·5	2·5
				2·0	1·5
				1·5	1·5
				1·0	1·0
				0·5	0·5
				3·0	3·0
				2·0	2·0
				1·5	1·5
				1·5	1·0
				1·0	0·5

TABLE I. Light and Electron microscope measurements of the granules in the visual components of the median eye in *E. modestus*.

Dimensions of:			
Spherical Granules		*Group of Spherical Granules*	
Length μ	*Width μ*	*Length μ*	*Width μ*
0·90	0·7		
0·95	0·69	1·62	1·28
0·95	0·69		
0·74	0·55		
0·67	0·51		
0·67	0·52		
0·60	0·43	2·48	1·66
0·48	0·32		
0·48	0·38		
0·73	0·51		
2·11	1·27	*An individual unit*	
0·86	0·58		
0·89	0·59		
0·64	0·46		
0·55	0·46		
0·52	0·33	3·49	1·87
0·51	0·35		
0·42	0·34		
0·43	0·34		
1·84	1·64	2·62	1·87
1·41	0·92		

TABLE 2. Electron microscope measurements of the granules in the visual components of the median eye in *B. balanoides*.

As the spherical granules occur in groups with relatively small space between each individual, one would expect the whole group to react to PF, and hence under the light microscope a group comprising of several individual units, appears as one purple mass. As noted above, under the light microscope there is a variation in the size of the granulations. This could be explained by the number of spherical granules comprising each group.

The actual structure of the spherical granules has not been finally evaluated as staining procedures have not yet been employed which would enable high magnification electron micrographs to be obtained. Certain facts as to their nature, however, have come to light. They appear to consist of a membrane enclosing many smaller densely packed inclusions which may or may not be vesicular (see plate VII). (Droplets of neurosecretory material are typically enclosed by a double membrane forming a vesicle). It is not yet known whether the membrane of either the enclosing structure or the individual members inside are double or single. There is evidence that the membrane of the enclosing structure produces finger-like outgrowths and that the small inclusions (plate VIII) pass either up or down them.

In the electronmicrographs of *E. modestus* (plates IX and X), the rhabdome and nuclei of the visual cells are easy to identify but the granulations appear to be very different. They are present as electron dense structures which are apparently grouped together in clusters, surrounded by a relatively large space. Measurements have been carried out of the area occupied by the granules and also the dimensions of the space enclosing the granules. The dimensions of the electron dense granules are too small to correspond to the granulations at light microscope level, but the dimensions of the space enclosing them does approximate to the size of the granulations.

The stains which are used to demonstrate neurosecretion are unfortunately, not specific. As we have seen, paraldehyde fuchsin stains the rhabdome as well as the granules in the cytoplasm of the visual cell. Many other structures within the animal are also stained positively with this stain. For this reason, histological criteria are not sufficient in determining whether a cell is neurosecretory or not; a physiological process (in this case moulting and metamorphosis) has to be related with a cyclical activity in the neurons producing the secretion. It should be possible to alter the cycle of production by varying experimentally the conditions under which the animals are kept, for example by exposing them to either constant dark or light, by alterations of temperature or feeding. Some larvae have been kept under conditions of constant dark for a period of up to three weeks, and samples withdrawn at intervals from the experimental batch and controls which were kept under normal light and dark conditions.

The hundreds of sections involved in this experiment make the analysis of results a long drawn out affair but so far no differences have been found in the granules in the constant dark larvae compared to the control group.

The term " neurosecretory " can be applied to two types of secretions, the first are hormones, the second are called chemical transmitters or neurohumours. Chemical transmitters are released at nerve endings where they cause muscle to contract. Common examples are noradrenaline which increases the heart rate and acetyl choline which slows it down. It would appear that the granulations present in the visual cells are concerned with the photo chemical reaction. Although the term neurosecretory could be applied to them, they are probably not the site of hormone formation. They could, however, be the site of neurohumoural synthesis.

The neurohormones of other species are characterised by being rich in aminoacids called cysteine and cystine and various histochemical tests are being made to see whether this substance is present or not.

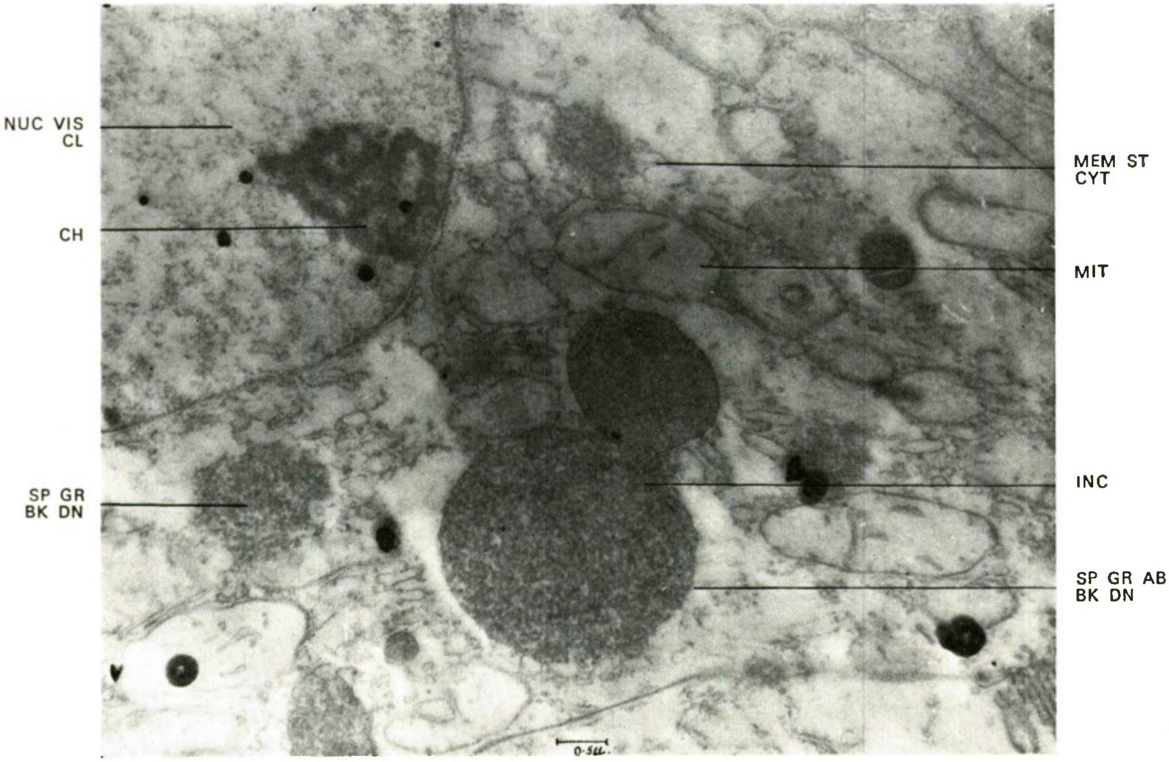


Plate VII. Higher magnification electronmicrograph of spherical granules.

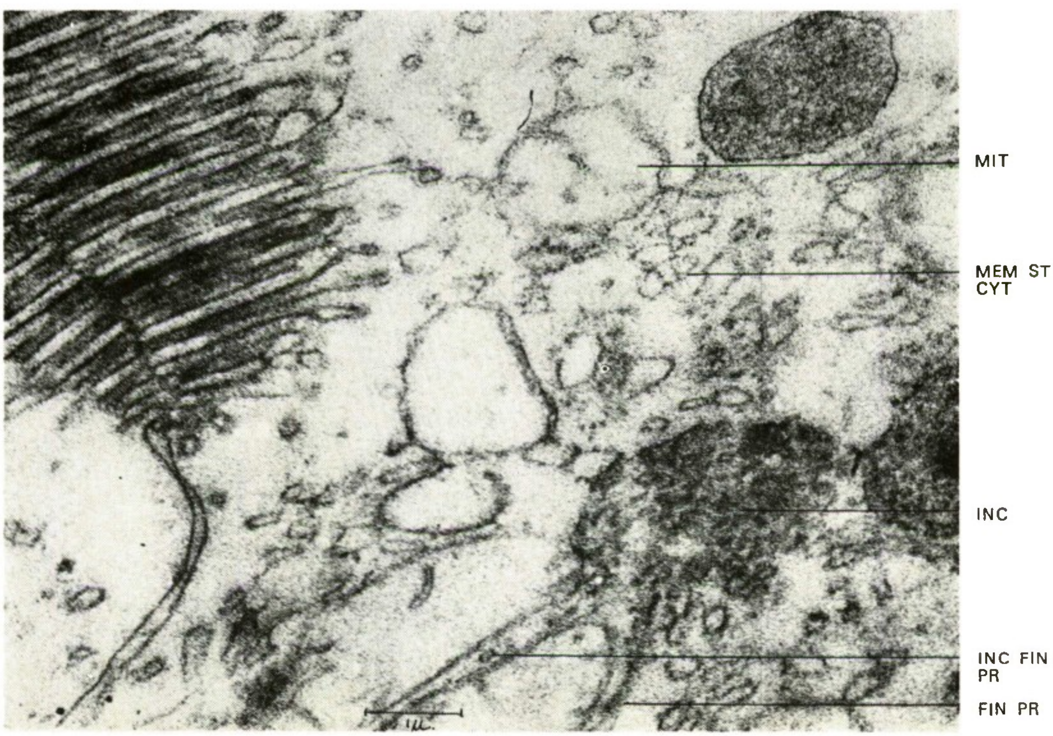


Plate VIII. Electronmicrograph of spherical granule giving rise to finger-like processes.

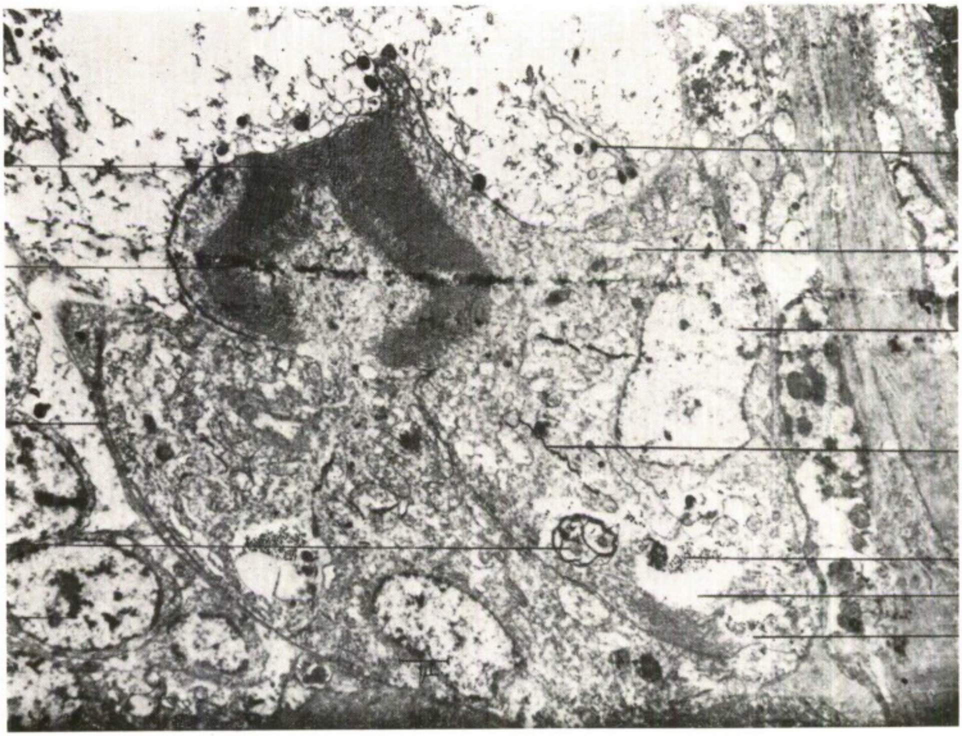


Plate IX. Electronmicrograph of L.S. through part of Median (Naupliar) Eye of *E. modestus*

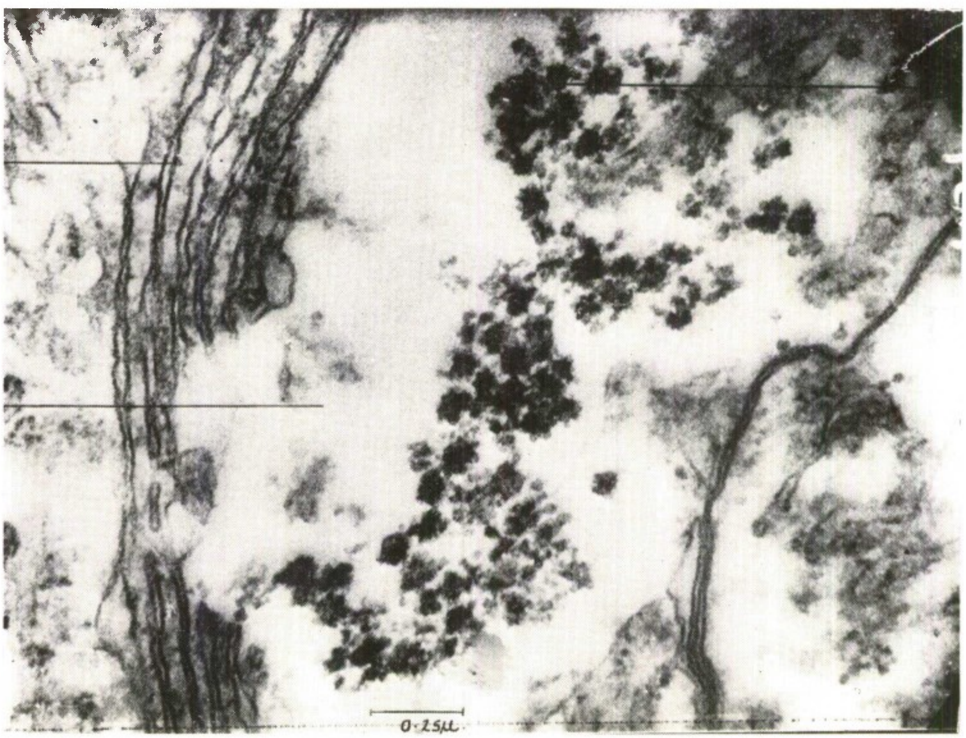


Plate X. Electronmicrograph of granules in the possible nerve ending.

Examination of a living nauplius larva under the microscope reveals two small unjointed appendages situated at the anterior end of the animal. These are the frontal filaments. In the sixth stage nauplius the frontal filaments become incorporated to form a complex with the compound eye. In the cypris the frontal filaments have become fully incorporated with the compound eye and are entirely internal, being directed posteriorly. The function of the frontal filaments is disputed. Some authors, Walley (personal communication) believe that they are entirely sensory in function, but Kauri has put forward evidence that they may have a neuroendocrine function.

The base of the frontal filament (Fig. 3) contains two different types of structures. In the anterior region there is a group of bipolar nerve cells, presumably sensory. The distal processes from the cells pass into the filament and the proximal ones into the filament nerve. Immediately caudal to these cells is a sac-like structure. Within this structure is fibrous tissue inside of which silver staining reveals small end bodies 1 - 2 μ in size on nerve fibres that come from the lateral lobe of the brain. Chrome haematoxylin reveals phloxinic granules to be present. Kauri believes that the filament bases have a typical sensory-papilla X. organ position and innervation. Such organs are part of neuroendocrine systems and either store neurosecretions or produce secretions themselves.

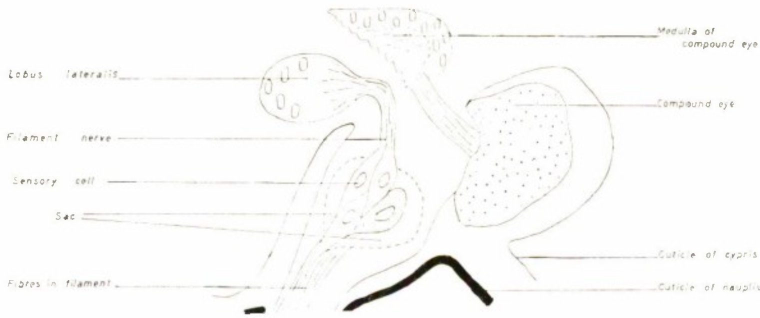


FIG. 3.

Diagram of traverse section through filament base in VI stage Nauplius (After Kauri).

The filament nerve connects distally to a group of bipolar neurons in the lobus lateralis of the brain. The nuclei of these neurons are comparatively larger than those of ordinary neurons. The present author believes that the bipolar neurons may be a possible site of neurosecretion and that the filament base could be a store. Paraldehyde fuchsin staining, however, has not revealed PF positive granules in the cytoplasm of the bipolar neurons. Tests for cystine have shown a slight positive reaction for the filament bases and more searching histochemical tests are at present being carried out in this region. If these tests confirm these findings, the filament base presents itself as a site of hormone synthesis.

It would be premature to conclude that a neuroendocrine mechanism is present in barnacle larvae; more evidence is required before such a mechanism can be confirmed. The actual change from one larval stage to the next involves the moulting of the outside cuticle. Walley (personal communication) has put forward evidence that this does not occur by somatic cell division alone but involves water uptake. The uptake of water in other animals has been shown to be under hormonal control.

Carlisle and Knowles (1959) working on larger crustaceans have shown that the control of moulting depends on the balance of two hormones, a moult inhibiting and a moult accelerating hormone. The moult inhibiting hormone when present in relatively larger concentrations prevents moulting; a decrease in moult inhibiting hormone followed by a simultaneous increase in the concentration of moult accelerating hormone results in the onset of procedysis, the first stage in the moulting cycle. On this basis one would expect several hormones to control the processes of moulting and metamorphosis in barnacle larvae.

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OBITUARY

DR. R. H. PURCELL, C.B., Ph.D., F.R.I.C.

It is with deep regret that we record the death of Dr. R. H. Purcell who died at his home in Wiltshire on Tuesday, 8th July, 1969 at the age of 64.

Dr. Purcell retired on the 31st May, 1968 following a long and distinguished association with University and Naval Science culminating in his appointment as Chief of the Royal Naval Scientific Service.

Graduating from the Royal College of Science, South Kensington, with a First Class Honours in Chemistry in 1924, he subsequently worked under Professor H. B. Baker, F.R.S. and gained a Ph.D. degree in 1927.

After two years abroad under various University Fellowships, he was appointed lecturer in Physical Chemistry at the Royal College of Science in 1929, and later assumed charge of the teaching laboratories in that subject. During this period his interests in chemical research were widespread and covered such fields as intensive drying of pure materials, phase rule studies, properties of heavy water and free radicals.

Although he retained his association with the Royal College of Science until the end of World War II, from 1939 onwards he was largely engaged on defence research. Following a short time working for the Ministry of Supply he became interested in naval problems and was appointed Scientific Adviser to the then Department of Miscellaneous Weapons and Devices, Admiralty. His services to the Admiralty became full time in 1944 and on the formation of the R.N.S.S. after the war he transferred to the then Department of Aeronautical and Engineering Research and was responsible for the organisation of materials research and development work.

After periods of attachment to A.M.L. and A.R.L. he was appointed Deputy Director of Physical Research, Admiralty in 1951.

In March 1954, Dr. Purcell left the Admiralty to become Chief Scientific Adviser to the Home Office, a position he held until 1962 when he returned to Naval circles on being appointed Chief of the Royal Naval Scientific Service in succession to Dr. H. F. Willis.

During his tenure of office as C.R.N.S.S., the increasing tendency towards centralised control of military policy and spending placed a progressively greater constraint on the individual Services and their supporting Scientific staff. Throughout this difficult period and in spite of failing health, Dr. Purcell consistently defended the interests of the R.N.S.S. and created the conditions in which it could and did flourish. His great understanding and respect for the individual dominated all his dealings with personnel, which occupied a large proportion of his time. He always made himself available to any member of the staff and gave them a courteous hearing and invariably sound advice. Some also profited by a lunch at the Atheneum.

Retirements

L. W. LAMBERT, R.N.S.S.

Mr. L. W. Lambert retired from Admiralty Service on 30th May, 1969 after having spent nearly all his working life in Government Service.

He joined the R.A.F. as an Aircraft Apprentice in 1922, passing out as a Wireless Operator Mechanic. At the end of 1938 he was accepted for the Admiralty Civilian Shore Wireless Service and found himself back at Flowerdown, which was the Electrical and Wireless School in his R.A.F. days. He served at Flowerdown until 1941, except for a three months spell at Lydd, on Romney Marshes in charge of the Post Office M.F./D/F Station.

Transferring to the Admiralty in 1941, he was responsible for the training of personnel who maintained equipment on V.H.F. sites on the South and East coasts, which were manned by W.R.N.S. linguists. He was also responsible for the testing, aligning and calibration of V.H.F. receivers, used mostly in large private houses, also he gave instruction in practical work to a number of W.R.N.S. radio mechanics.

After the war he was transferred back to Flowerdown, working on development of teleprinter links with Naval stations abroad, which were using high speed morse. He then moved to Lythe Hill, Haslemere, in 1950 (having been appointed to the R.N.S.S. in 1947) joining the Engineering Services Section, working with Projects on Radio and E.W. Equipments.

He was Assistant Treasurer of the A.S.W.E. Sports Club and one of the organisers of the Music Club, subsequently being made Secretary. He will be missed by many whose hobby is music and record collecting.

He is now retiring to the New Forest (to the small village of Everton, three miles west of Lymington and one-and-a-half miles from Milford) and hoping to do plenty of walking and music making with just a little gardening.

W. G. D. MANNS, R.N.S.S.

Mr. W. G. D. Manns, Ex-Leading Draughtsman, retired on 30th May, 1969 after 49 years in Admiralty service. Starting as an M.E.D. Apprentice in 1920 he joined the Drawing Office in 1936 and the majority of his experience was in the Mine Design sphere. He transferred to A.S.W.E. in 1959 under the "Way Ahead" programme. Here, his drawing office experience was used in liaison services with Development Contractors Drawing Offices.

In his retirement Bill Manns intends to devote more time to motoring as a pleasure rather than a duty. The photograph shows Mr. Manns (left) being presented with a cheque by Mr. A. Lambert, Drawing Office Manager, A.S.W.E., on behalf of his many colleagues with which it is intended to purchase a transistor radio.

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S. FIRTH, R.N.S.S.

Miss Stella Firth retired from SSP(N) on 26th June, 1969, after 26 years in the Civil Service, all but three of these with SSP(N). After her education at Cheltenham Ladies' College and the Royal Holloway College

(London University) where she graduated in 1925, she spent many years in industry (including some years on the *Daily Mirror*) before joining the Ministry of Aircraft Production as an AIII at Fighter Command HQ in 1941. She came to the Admiralty in 1943 as a TEO, became a new style Experimental Officer in 1946 and was promoted SEO in 1949.

Her wide experience and her sympathetic but realistic approach and outlook made her particularly well suited to personnel work. Her charming and imperturbable manner on the telephone must have been familiar to many in the R.N.S.S.—both new recruit and Establishment Head—she dealt effectively with all alike. Any newcomer to SSP(N) quickly found her a mine of information, always willing to help or advise, and always a valued and agreeable colleague.

Miss Firth will continue to live in London and maintain her association with her Church activities in which she was deeply interested. We wish her many happy years in active retirement.

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Notes and News

Admiralty Experimental Works

In May, Mr. M. S. Chislett visited the Hydro-og Aerodynamisk Laboratorium, Lyngby, Denmark for discussion on a joint design of the horizontal planar motion mechanism which is expected to be suitable for use at Lyngby and A.E.W.

A lecture by Admiral Sir John Frewen, Commander in-Chief Home Command, held at A.S.W.E. was attended by the Superintendent and Chief Scientist of A.E.W. together with five other officers.

The B.T.T.P. meeting held at Vickers House on 6th June was attended by Mr. A. J. Vosper (Chairman) and Mr. P. W. Hunt (Secretary). A.E.W. was represented at lectures given during the three day International Marine and Shipping Conference. Visitors to A.E.W. during June included members of N.S.R.D.C., U.S.A., Mr. Soar, Scientific Advisor Western Fleet, and three representatives from Germany who were taking part in the Anglo-German collaborations in scientific studies.

Mr. N. Hancock, D.W.D., Mr. W. G. Perry, D.D.D.C./A., and Mr. K. G. Evans, Superintendent N.C.R.E., visited A.E.W. during July for the Liaison Meeting. In the same month Mr. E. P. Lover accompanied by staff from U.C.L., visited Lyngby, Denmark and Delft and Wageningen, Holland.

Admiralty Oil Laboratory

On Tuesday, 15th July, 1969 Mr. D. Stewart Watson, D.C.S.(N) with Mr. S. A. Bolshaw, Scientific Adviser to D.G.S., visited A.O.L. when they saw a cross-section of the work in hand and met a number of the staff. The day was unusually warm and sunny and the layout and pleasant setting of the laboratories was seen to best advantage.

The Tripartite Conference held every two years between the R.N., the U.S.M. and the Canadian Armed Forces (Sea), C.A.F.(S) to discuss Naval Fuels and Lubricants took place in Washington from 5th to 13th May, 1969. On this occasion the R.A.M. also sent a delegation. A.O.L. was well represented in the R.M. delegation, the meetings being attended by Mr. R. P. Langston, Superintendent accompanied by Dr. D. Wyllie and Mr. J. Ritchie. The Conference, to which selected Industry members are invited, took place in the Washington Navy Yard except for the last two days which were at Naval Ship Research and Development Center, Annapolis, Maryland, and which were restricted to Government Staff.

Following the Conference the A.O.L. contingent split up and visited laboratories. Mr. Langston went to San Antonio, Texas, to visit the Southwest Research Institute and then on to San Francisco to the U.S. Shipyard Laboratory, Mare Island. Dr. Wyllie and Mr. Ritchie visited the Surface Chemistry and Fuels Laboratories of the Chemistry Division of the Naval Research Laboratory, Washington, after which Dr. Wyllie visited the Naval Ship Engineering Center and the Naval Air Engineering Center at Philadelphia and a major oil company laboratory, Texaco Research Center, Beacon, New York. Meantime Mr. Ritchie visited N.A.S.A. Lewis Research Center, Cleveland, Ohio, the Canadian National Research Council, Ottawa, and the Canadian Naval Engineering Test Establishment, La Salle, Montreal.

The Annual Meetings of the N.A.T.O. Fuel and Lubricant Working Parties took place in Brussels from 4th to 11th July, 1969, and were attended by Dr. Wyllie of A.O.L. On the following Monday two U.S.N. delegates, Cdr. J. J. Ryan Jnr., U.S.N., and Mr. E. C. Davis, both from the Naval Ship Engineering Centre, Washington, started a round of visits in the U.K. with a visit to A.O.L.

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Admiralty Materials Laboratory

Admiral Sir Horace Law, K.C.B., O.B.E., D.S.C., Controller of the Navy and Mr. B. W. Lythall, C.B., Chief Scientist (Royal Navy) accompanied by Capt. L. H. Oliphant, D.S.C., visited A.M.L. on 11th March, 1969. They were introduced to key members of the staff and were shown selected items of the research programme.

A paper by Dr. C. A. Parker (" Spectrophosphorimeter Microscopy: An Extension of Fluorescence Microscopy") was published in the Analysis. 94(1969)161.

A number of members of A.M.L. attended the 3rd Inter Naval Corrosion Conference in London from 14th - 18th April, and the following paper contributed:—

" The control of Microbiological Deterioration in Marine Services "—J. J. Elphick.

" Present and Future Full-Scale Land-Based Corrosion/Erosion Studies on Ships' Sea Water Piping Systems "—D. J. Godfrey, B. Angell and A. F. Taylor.

" The Control of Corrosion in Marinised Gas Turbines."—J. F. G. Condé.

The 23rd Annual Power Sources Conference at Atlantic City, New Jersey, May 1969 was attended by Dr. R.

Holland of A.M.L. who also visited several laboratories in North America to discuss recent advances in the development of high energy density batteries

Dr. D. J. Godfrey visited the U.S.A. over the period 10th - 30th May 1969 in connection with the 1969 meeting of T.T.C.P. Panel P2—"Inorganic Non-Metallic Materials" held in San Francisco to discuss defence applications of ceramic materials. Visits were made to defence contractors in the San Francisco areas with the Panel, and under the sponsorship of N.R.D.S. to U.S. firms interested in the silicon nitride technology developed at A.M.L.

Mr. D. Birchon visited the U.S.A. from May 9th - 21st, 1969 as the U.K. National Leader of T.T.C.P. Panel P4 "Methods of Test and Evaluation (of materials)". A week's business meetings at the U.S. Army Materials and Mechanics Research Center, Watertown, Mass. was supplemented by technical visits to N.A.S.A. to see advanced instrumentation techniques, A.V.C.O. to look at non-destructive testing of composites and to Pratt & Whitney for the study of quality control procedures in an area of sophisticated engineering.

Members of T.T.C.P. Sub Group P Working Panel No. 3—Organic Materials—visited A.M.L. on Thursday, 8th May, 1969 and were shown the work of the laboratory on Microbiological Deterioration of Materials, G.R.P. and C.F.R.F., Drag Reduction Polymers, Material aspects of Fuel Cells and Fresh Water Production by Reverse Osmosis, Non Destructive Testing of G.R.P. and Analytical Techniques applied to Oil Slick Identification and Oxygen Determination in Degraded Polymers.

Dr. R. K. Packer, P.S.O., joined A.M.L. on transfer from A.U.W.E. on 2nd June 1969.

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Admiralty Surface Weapons Establishment

Mr. Eric N. Le Fevre read a paper entitled "Frequency Standards for HF Communications" at the 23rd Annual Frequency Control Symposium recently held by the U.S. Army Electronics Command at Atlantic City.

Dr. R. G. F. Taylor, published a paper entitled "Microwave Ultrasonics in Contemporary Physics", Vol. 10, No. 2 1969 (pp. 159 - 178) based on work done at A.S.W.E. Dr. Taylor is now at S.E.R.L.

On Thursday, 3rd July 1969, representatives of the National Press were welcomed by Mr. H. W. Pout, Director, and senior members of his staff. After a briefing on the work of the Establishment by the Director, they were shown various aspects of the current programme including Radars for Guided Weapon Systems, Gunnery Control and Aircraft Direction, Data Processing systems using automation principles, Special Electronic Warfare equipment and many kinds of Communication Transmitters, Receivers and Aerial Systems to meet the specialized requirements of Warships.

Mr. R. A. Ballard left A.S.W.E. on July 1st, 1969, after 25 years service. He has gone to the newly formed Civil Service Department as an S.P.S.O. in charge of a department responsible for Automatic Data Processing Applications in the Civil Service.

He joined the Establishment in 1944, at the age of 19 years, as a Temporary Experimental Assistant III. After several promotions he reached P.S.O. in 1960. Apart from a short period in the aerial group at Funtington, he has worked on data handling and display systems, and under Mr. Benjamin (now Dr. and Director A.U.W.E.) was a founder member of the first A.D.A. computer team. He became project leader for A.D.A. in H.M.S. *Eagle*; and in 1965 project leader in charge of A.D.A. computer programming for the new generations of ships led by H.M.S. *Bristol*.

He joins the Civil Service Department at its formation stage with the many challenging and stimulating problems of the post-Fulton era.

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Admiralty Underwater Weapons Establishment

At the annual naval base shooting competitions at Portland a team of apprentices, captained by an ex-apprentice, from A.U.W.E. beat 20 teams to win the Morse Cup; a cup presented by Captain (now Admiral) Morse in 1935 for competition by ships and establishments in the Portland area. The team, led by John Cavill consisted of John Stamp, Bill Bartlett, Alec Penfold and Dave Harris, all members of the A.U.W.E. Rifle Club. The event is a knock-out contest where each team (with 60 rounds of ammunition per team) run 50 yards and then fire over 200 yards with the semi-automatic S.L.R. at 12 target discs. A.U.W.E. teams previously won the Morse Cup in 1961 and 1962, while before that, the former U.D.E. won it in 1957, 1959 and 1960.

The U.K. was host country this year for the main series of meetings of the working parties of sub-committee "S" (A/S Detection) under the auspices of the tri-partite Anglo/French/Netherlands Collaboration Organisation. The meetings were held at A.U.W.E. during the week 28th April - 2nd May, and a wide range of topics was discussed, and demonstrations were laid on. About 20 French and Dutch scientists and naval officers attended.

This was followed on 20th - 22nd May by a series of meetings of the Technical Panel of the Mine Countermeasures Working Party and Sub-committee "M". The meetings discussed progress made by individual countries during the year, and the U.K. presented reports on current projects. A highlight of the visit was a skittles match held on the evening of 20th May.

Also held at A.U.W.E., on 24th - 27th June, was the 15th meeting of the A.S.W. and Torpedo Sub-Committee of the Anglo-French Joint Naval Committee.

The annual Official Cocktail Party was held at A.U.W.E. on 13th June, when the establishment entertained about 200 official and personal guests.

The Commander-in-Chief, Portsmouth, Admiral Sir John Frewen, K.C.B., gave a talk on "The role of the Navy" to an audience drawn from all grades on 26th June.

The Technical Directors and other senior officers from three United States Research Establishments, N.R.L.,

N.A.D.C. and N.U.S.L., visited A.U.W.E. on 19th June, and were given a brief but comprehensive insight into the establishment's work.

Sight-seeing trips around the fleet were arranged for A.U.W.E. staff when 40 ships of the Western Fleet, including the aircraft carrier *Eagle* and the nuclear submarines *Valiant* and *Warspite*, assembled in Weymouth Bay on 24th and 25th July.

Mr. C. P. Rigby, D.C.S.O., joined A.U.W.E. on June 1st, 1969, to become Head of the Engineering and Common Services Department.

Mr. Rigby, who is 56, graduated in mechanical engineering from the University of British Columbia in 1933 and then entered the engine works of J. Samuel White and Co. of Cowes as an apprentice and later, engineering draughtsman.

In 1942 he joined Engineer-in-Chief's Department, Bath, as a Temporary Experimental Officer, to deal with a variety of vibration and noise problems in turbine blading, gears and propeller shafts. Following establishment and promotion to P.S.O. he moved in 1948 to A.E.L. as head of the Gas Turbine Section and was concerned with development running of the original "Gatric" and various Rover and Turbomeca engines and research into the effects of residual fuel ash on blade materials.

In 1956 he returned to Engineer-in-Chief's Department as an S.P.S.O. in time to be involved in the turbine designs for the Dounreay prototype and H.M.S. *Valiant*. When the Ship Department was formed he became a member of Scientific Adviser's Group, heading the section responsible for Mechanical Engineering design problems and latterly giving special attention to improving the dynamic balance of nuclear submarine machinery with a view to reducing radiated noise.

Since 1966 Mr. Rigby has been with the Ministry of Technology as the D.C.S.O. Superintendent of the Machinery Group at the National Engineering Laboratory. The work of the group covers machine tools, engineering metrology, machine elements (*e.g.* oil and gas bearings, gears, etc.), oil-hydraulic power transmission components and systems, optical methods, computer programmes for numerically controlled machine tools and computer aided design. A.U.W.E. - N.E.L. co-operation has already been active in the last two named fields.

Arising from the special relationship between N.E.L. and the University of Strathclyde Mr. Rigby is currently a Visiting Professor of that University.

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Central Dockyard Laboratory

A Patent entitled "A Method for the Determination of Corrosion Rates by A.C. Polarisation Resistance Measurement" by M. N. Bentley and J. C. Rowlands has been published. The Patent Number is 1,150,416.

An article on the presence of a Sigma Phase in CN-Ni-Mn-Fe-Al-Cr casting alloys, by B. N. Hall of this Laboratory and Dr. R. A. Farrar of Southampton University, was published in the *Journal of the Institute of Metals*, June 1969.

Mr. J. C. Rowlands attended the International Nickel Marine Corrosion Conference at Biarritz on 2nd - 4th June, 1969.

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Naval Scientific and Technical Information Centre

Mr. A. H. Holloway attended the Annual Conference of the ASLIB Electronics Group from 27th - 29th June. Two other members of the R.N.S.S., Mr. Pottage of A.S.W.E. and Mr. Gardiner of S.E.R.L., were also present. The papers presented provided a useful blend of the special problems of information work related to electronics, cost effectiveness and superconductivity.

Following the retirement of Mr. A. H. Holloway on 30th September, Mr. H. L. R. Hinkley, Head of N.S.T.I.C., becomes the Navy Department representative on the AGARD Technical Information Panel, which is to hold its next Conference in Ottawa and Washington in September. Whilst in the United States Mr. Hinkley will take the opportunity of visiting B.N.S. to discuss the exchange of scientific and technical information between the U.S. Navy and the Royal Navy.

Harry E. Pebly, Jnr., Chief, Plastics Technical Evaluation Center, Picatinny Arsenal, Dover, New Jersey, U.S.A. visited N.S.T.I.C. on Thursday, 19th June, 1969, to discuss collaboration and exchange of information between the two establishments.

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Services Electronics Research Laboratory

Mr. N. S. Gardiner attended the 11th Conference of the A.S.L.I.B. Electronics Group at Westcliff-on-Sea, June 27 - 29.

Mr. M. J. Beesley attended a conference on Optical Instruments and Techniques at Reading University from July 14 - 19.

Dr. C. H. A. Syms visited the U.S.A. between July 16th and August 8th, during which time he visited a number of laboratories concerned with photocathode research, and attended the University of Rhode Island Summer School on Photo-Electronic Imaging Devices at which he presented an invited review paper on Photocathodes.

Mr. S. D. Lacey attended an I.C.S.L. course on Algol Computer Programming from September 2 - 5.

Dr R. Allen and Mr. R. F. Webber attended the I.P.P.S. Conference on "Atomic Collision Phenomena in Solids" at the University of Sussex, September 7 - 12.

Dr. H. M. Lamberton attended a conference on "Non-linear Optics" at Queen's University, Belfast, September 8 - 12.

Dr. C. H. Gooch and Messrs. R. Bottomley, K. G. Hambleton, H. Tarry, A. Wallace and R. F. Webber attended the third Conference on Solid State Devices at Exeter University from September 16 - 19. Dr. Gooch presented a paper by M. C. Rowland and himself on "Red-emitting Gallium Phosphide Diodes on Bulk Single Crystal Material; Mr. Hambleton presented a paper "Fabrication of Semi-conductor Diodes on Copper Heat Sinks"; and Dr. R. A. Giblin read a paper by Messrs. Hambleton and Tearle and himself on "A Simple Pictorial Analysis of Large Signal Behaviour of Avalanche Diode Oscillators". Dr. Giblin is now at the Department of Electronic and Electrical Engineering at University College, London.

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Book Reviews

Algebraic Coding Theory. By Elwyn R. Berlekamp, published by McGraw-Hill Book Co., 1968. Price 164s.

This is a formidable looking book, which at a cursory glance, seems not to comply with the author's claim that it is a text that can be used by beginning graduate students and even advanced undergraduates. On closer examination, however, it is so written that the reader equipped with no more than the rudiments of linear algebra should be able to cope with most of the material without too much difficulty.

There is presently, for obvious reasons, a considerable and increasing interest in digital information transmission, yet any serious attempt at including coding theory in the syllabus of undergraduate engineers is a very recent inovation at most Colleges; therefore, no doubt, there are many whom have graduated fairly recently who feel that they have been left completely behind in the field. A reading of the first five chapters should do much for their moral, particularly in view of the fact that most of the development of this subject has been at the hands of engineers.

These early chapters set the scene and introduce the terminology and the necessary amount of so-called modern mathematics which coding theory requires. The author contends, with considerable justification, that it is easy to overestimate the overlap between this field and those fields with which it is normally associated, i.e. information theory and abstract algebra. As he points out, coding theory is best categorized as a branch of the emerging field of discrete numerical analysis.

This being the case, the main bulk of the book is concerned with algorithmic topics connected with various coding schemes, notably cyclic coding. The main stream of work so far developed in coding theory has been directed almost from the outset to the simple and easily implemented devices, particularly the crucially important decoding hardware. This has been, in some respects, a somewhat pious hope but these essential practical aims have been kept in mind throughout this book.

This is not to say that practising engineers will be able to use this book as a recipe book. It is essentially a textbook and not a handbook, albeit one of encyclopaedic proportions. This is undoubtedly the most comprehensive text on coding theory available, it is extremely well written and has an extensive bibliography. The reviewer feels that the last words on the book should be a quotation from a survey paper by F. J. MacWilliams given at a Symposium at the University of Wisconsin which is as follows:

The Berlekamp book you must get
To belong to the cyclic set
It purports to state
All knowledge to date
And a lot that is not known as yet.

J. O. Flower

Optical Physics. By S. G. Lipson and H. Lipson. Pp. xii + 494. Cambridge University Press, 1969. Price 75s.

In their preface to this book, the authors state that they have tried to explain the principles of optics, but that wherever possible they have emphasised the relevance of these principles to other branches of physics. Thus, this is not a textbook dealing purely with optics and optical systems, but covers a wide range of topics broadly based on optical principles. Descriptions of many classical experiments in optics have been omitted because they are adequately covered elsewhere, and elementary geometrical optics, aberrations and some optical components have been relegated to appendices.

The book begins with a brief historical introduction, followed by chapters on Wave Theory, Fourier Theory and Electromagnetic Waves. As might be expected, these chapters contain a fair amount of mathematics and, in order to benefit fully, the reader needs some knowledge of advanced mathematics including vector algebra. However, the clarity of the presentation and the numerous helpful illustrations, do much to ease the passage of the reader through the more difficult sections. The optics of anisotropic media are fully discussed both theoretically and with reference to practical application. There are also comprehensive chapters dealing with the more widely known phenomena of Interference and Diffraction. These include descriptions of a number of interferometers and also a discussion of various types of diffraction grating and the effects of periodic and random errors. Further chapters deal lucidly with the subjects of Coherence and Dispersion and there is an interesting section on Holography.

The Schröedinger wave equations is explained in a chapter entitled "Quantum Optics", and the elements of Perturbation Theory are developed and applied to maser and laser action.

The last part of the book deals with some applications of optical ideas. The use of visible light for the testing of flat surfaces is mentioned and this leads naturally to a discussion of methods for the examination of matter. It is shown that the limit of resolution of a microscope can be extended by the use of a shorter wavelength radiation and the techniques of electron, x-ray and neutron diffraction are described. There are also sections covering Astrophysics, Radioastronomy and an introduction to Magnetoionic Theory.

The prominent features of this book are the clarity and quality of the presentation, including the very large number of diagrams, and the wide range of subjects covered. The authors' approach to the subject shows clearly how optics is inter-related with other branches of physics. The standard of the text is advanced undergraduate or graduate level but it should also be useful to specialists in other fields requiring an introduction to optical techniques.

R. G. F. Taylor

Series Expansions for Mathematical Physicists. By Herbert Meschkowski. Pp. ix + 173. Edinburgh; Oliver & Boyd Ltd., 1968. Price 21s.

As the author states, this book, one in the series of University Mathematical Texts, is more than physical in content. It is also a translation of a German text the author being a Professor in the Free University of Berlin.

The main emphasis is on orthogonal series (of great interest to mathematical physicists) and a subsidiary aim is to give an introduction to Hilbert Spaces as far as is possible without the use of Lebesque integrals. Again Hilbert spaces are of interest in theoretical physics.

Newton's interpolation formula is discussed in the first chapter and then generalised to cover four types of interpolation problems not all of which necessarily have solutions. The next two chapters discuss Fourier series and their application. Sectionally continuous and sectionally smooth periodic functions are introduced and the latter shown to have a Fourier series representation except at the points of discontinuity. That all continuous functions cannot be represented by a Fourier series is demonstrated with an example by Fejér. These two chapters include as well the complex form of the Fourier series, Bessel's inequality, the concept of a saltus, and a discussion of the isoperimetric problem (the maximisation of an area enclosed by a set of closed rectifiable curves) are treated by Hurwitz. Some treatment of the converse problems of finding a function represented by a given trigonometric series is also included.

Fourier series lead naturally to orthonormal systems which are of great value in solving practical problems. The scalar product of two functions is introduced which may be generalised to include complex functions and positive weighting functions. In this way orthonormal systems are discussed with varying ranges for the scalar product and weighting function. The examples treated are Chebyshev, Legendre and Laguerre polynomials.

The completeness of a sequence of orthogonal functions is of importance and the concept is defined in Chapter V where also the completeness of some of the more important orthonormal systems is established.

The only chapter with appreciable physical content is that devoted to eigen value problems in physics. These are of interest since many boundary value problems have solutions in terms of orthogonal eigen functions determined by the problem. The concepts of operators especially Hermitian operators with real eigen values are introduced in this chapter and the main physical problems studied are the solutions of Schrodingers equation for a linear oscillator and the transverse vibrations of stretched string. This latter problem introduces integral equations of the first and second kind with respect to the unknown quantity and thus introduces Kernel functions. This problem gives rise to two types of problem in an infinite system of linear equations and a method of solving one of these is given in another chapter and illustrated with Mathieu's differential equation.

The topic of Hilbert spaces is introduced from Fourier series by means of Hilbert sequence space.

Stripped of its mathematical subtleties a Hilbert space has much in common with vectors—a function being correlated with a point in the space represented by the coefficients of its expansion in a series of functions. The definition of an inner product space is given axiomatically in the text then a Hilbert space is related to it by further restrictions of a Cauchy sequence and a simple metric between points. Many well known examples of a Hilbert spaee are given and shown to be separable. The need for the use of the Lebesque integral is then pointed out in order to extend the set of quadratically integrable functions which can form a Hilbert space.

The last chapter is devoted to the theory of reproducing Kernels where the integral operator leaves the transformed function unchanged. A reproducing Kernel function can be associated with a Hilbert space and the properties of such spaces are outlined in this chapter.

This book, with its strong advice to physicists not to discard as trivial these functions often called pathological, since they now have practical interest in physics, can be strongly recommended as an introductory text where mathematical vigour is achieved but the needs of physicists for clarifying examples is not ignored.

R. A. M. Bound

A History of Nautical Astronomy. By Charles H. Cotter. Pp. xii + 387. London; Hollis and Carter, 1968. Price 63s.

Captain Cotter is now a senior lecturer on maritime studies and he has written a readable business-like book, which provides what its title promises in a manner which is attractive to the non-specialist and also provides the necessary mathematics for the specialist; in any highly technical work this always presents a serious problem, for where the earlier steps are simple enough the later advances are only intelligible to readers who can follow the computations. The book, moreover, comes at a time when celestial navigation, having reached a high state of development, shows every sign of outliving its practical usefulness, having been largely superseded by the radio aids. It is interesting to speculate on the extent to which the classical navigational instruments were 'black boxes' to many of the seamen who used them just as the radio equipment is to the navigators of today, and the present book is largely designed to combat such an attitude of mind.

Chapters are included on early developments, astronomical methods of time measurement at sea, altitude-measuring instruments, corrections to altitude measurements, methods of finding latitude and longtitude, position-like navigation and navigation tables, and there are short appendices on spherical astronomy and spherical trigonometry. These last are necessary to complete the work since their subjects are likely not to be well known to the general reader but also to many mariners who have navigated by their aid according to the rules without fully understanding what they were doing; this aspect is emphasized by the heavy weather which is sometimes made of simple arithmetical operations as for example on page 214.

Each chapter gives a clear account of the development of its subject, nearly always from sources which the author has actually studied, since there are a few guarded references to works which he has evidently not seen and there seems to be on occasion a note of regret as of the fact that radio time-signals have superseded the use of more sophisticated methods of finding longitude, though full credit is always given to the merits of more readily applied methods and to the simplification of the navigator's task.

While the technicalities of the subject are likely to restrict the book for the most part to those to whom it has a practical relevance, the writing is clear and straightforward, and the volume can be commended to the general reader who wishes to grasp the problems and difficulties of the historical navigators and the ways in which they were tackled.

A. H. Holloway

Optimization in Control Theory and Practice. By I. Gumowski and C. Mira. Pp. ix + 239. Cambridge: Cambridge University Press, 1968. Price 65s.

The authors of this book see a gap in communication between designers of control systems and theoreticians and believe that the first step in bridging this gap must be taken by theoreticians. This then is the main aim of the book and consequently it is mainly mathematical in outlook although not divested of physical meaning. In the introduction the authors give a clear and concise summary of its contents and its main conclusion, i.e. that all presently available optimization techniques, Euler's equations, Pontryagin's maximum principle and Bellman's dynamic programming are

merely particular cases of a boundary value problem studied by Caratheodory and can be formulated in terms of a generalised Huyghens principle.

To return to the gap between control theoreticians and designers, the authors trace the first crack to Cauer's introduction, in 1926, of idealised circuits and meromorphic functions into electrical engineering. The crack becomes a chasm in the modern linear system theory mainly developed in the U.S., and based on Laplace transforms, pole and zero techniques and root locus diagrams. The claim is made that practical realism is absent in these idealised sophisticated approaches. It is stressed that most plants requiring control are time varying, non linear and with distributed parameters-problems not soluble by modern linear system theory. Although probably no stigma is intended to be attached to the U.S. as the main users of the linear theory it is worth mentioning that similar thoughts have arisen in the U.S. and are apparent for instance in the writings of Bellman. Nevertheless it will be diffcult to wean a large body of electrical engineers away from their mother techniques although this should not prevent someone making the effort. This book is one such attempt.

The book consists of only five chapters but the first is long and its main purpose is the discussion of models of the problems requiring optimization. It is emphasised that the model must be insensitive to all forms of perturbations of which a number are studied in detail. There is a discussion of admissable solutions to optimization problem. The insensitivity to perturbations introduces the concept of an apriori model defined as one in which a reasonable knowledge (not a precise one) of the components allows the prediction of the realistic properties of the whole. This is to be contrasted with the so-called Phenomenological models.

The text is mainly mathematical but is written in keeping with the aim of closing the gap in language understandable by engineers prepared to accept new concepts. Most of the mathematical nomenclature used in functional analysis (the central techniques employed) is clearly explained in an appendix.

The problems requiring optimization are formulated in terms of explicit *functionals* not functions, with restraints and boundary conditions. Only simple explicit functionals are used and a large section of the book is devoted to clarifying the concepts and properties of such functionals and why their properties (especially with regard to extrema) are different from functions. The functionals are composed of the state functions, the control functions and subsidiary constraints, and the physically useful optimization demands, after Hadamard, that the functional be locally continuous, a concept which is fully explained. It is shown that optimization problems may be equivalently formulated in a number of ways analogous to the formulation of conservative mechanical systems in either Hamilton or Lagrange forms. In general it is shown that they may be formulated in terms of a boundary value problem associated with Caratheodory's partial differential equation and expressible in terms of a generalised Huyghen's principle.

The last chapter is devoted to methods of obtaining approximate solutions to the optimization problems since exact solutions are usually unobtainable.

The book deserves to be read by engineers for its break with traditional control theory. Although a mathematical text the mathematical developments will easily be comprehended by any engineer who has studied the calculus of variations. Great care has been taken in the book not to overgeneralise uselessly—a fault the authors see in much of the publications on modern mathematics.

R. A. M. Bound

Probability and Hypothesis Testing. By L. N. H. Bunt and A. Barton. Pp. 207. London; George G. Harrop Co. Ltd., 1967. Price 27s. 6d.

Apparently this is an English version of a book which was written as part of a project introducing the teaching of statistics and probability into a group of grammar and technical high schools in the Netherlands. It was first published (in Dutch) in 1956, and later modified in the light of experience. It is assumed that readers will have mathematical ability roughly equivalent to O-level Elementary Mathematics. Furthermore the authors have intentionally restricted the contents to a few important topics, since their experience has shown that any attempt to range widely in the early stages is apt to produce a blurred impression.

The first chapter is designed to familiarise the reader with frequency distributions, their means and standard deviations, so that these concepts can be used in later chapters. Permutations and combinations are introduced in Chapter 2, and elementary probability in Chapter 3. Consideration of probability distributions leads quite naturally to the introduction of the binomial distribution in Chapter 4. In accordance with the authors' intention not to confuse the issue only one type of hypothesis testing is considered in Chapter 5. The purpose of this chapter is to give a method for dealing with problems involving the drawing of conclusions about the composition of a population when the composition of a sample is known. The method described uses the binomial distribution. In the final chapter it is pointed out that for a large sample the normal distribution is a very good approximation to almost any binomial distribution, and consequently the use of the normal curve is developed.

Within the authors' self-imposed limitations this is an excellent book, the selected topics are introduced in a simple clearly explained and logically developed manner. However, for the majority of members of the R.N.S.S. the treatment is a little too elementary, although anyone studying statistics for the first time may well benefit by an initial reading of this book before proceeding to more advanced texts.

The book contains a vast number of examples, clearly of value to the beginner, but, less obviously, of interest and amusement to the more advanced reader.

J. B. Spencer

Observations in Modern Astronomy. By D. S. Evans. The English Universities Press Ltd. Price 84s.

The author of this book is Chief Assistant at the Royal Cape Observatory, and he believes that many recruits to the astronomical profession have a very limited knowledge of optical observational practice. This he thinks is largely due to the unsuitable climate in many countries, as a result of which students for higher degrees pursue avenues of research in which they do not acquire skill in the rudiments of their profession. Hence, he hopes that his book will be a kind of manual for the student who aspires to be a working astronomer, or, on the other hand, satisfy the physicist who wants to know what goes on in observatories. Mr. Evans, who has worked for nearly twenty years as an observational astronomer in the optical field, explains how and why observations are made; he assumes some knowledge of physics, but not of astronomy.

The book begins with a study of various methods for determining the co-ordinates of position of astronomical bodies, for example, the transit circle procedure. Astronomical aspects of time are also discussed, and the use of the impersonal astrolabe of Danjon and photographic techniques described. The measurement and analysis of stellar radiation are dealt with in the second chapter,

and the third is concerned with inter-relations between observed quantities. The latter is an extremely interesting chapter in which consideration is given, among other things, to the magnitude and colouring of stars, the giants, white dwarfs, and stellar evolution.

Following on from the first two chapters, in which methods for determining the motions of stars with respect to the sun were considered, the transformation of axes to a system of more general validity is dealt with in chapter four. Obviously, most astronomical observations require very sophisticated and expensive equipment, but in one field an important contribution is still being made by amateurs using relatively simple equipment. This contribution is in the observation of variable stars, classified as pulsating, novae, supernovae or eclipsing types, and described in chapter five.

Another type of star is the binary (or multiple) variety, and there are now thought to be more of these than single stars. Their importance is that they provide a direct approach to the determination of stellar mass, and they can yield evolutionary information. Chapter six contains descriptions of the observational methods and subsequent analysis of the data obtained.

The topics of the last chapter are the Galaxy (our own) and the galaxies (others), not that ours is considered to be unique, in fact, there are an enormous number of objects in the same general classification. As in other chapters methods of observation and classification are described. This being a book about optical astronomy (which is responsible for revolutionary developments in this field) is only mentioned when it bears particular relation to optical observation.

This is a magnificent book, clearly written, well produced with some fine black and white plates, and a plentiful supply of references at the end of each chapter. Mr. Evans believes in writing about what he knows, and not what he thinks he ought to know, and he says that writing this book revealed to him the incompleteness of his knowledge. There will be few, if any, readers to whom this incompleteness will be apparent.

J. B. Spencer

Introduction to Control System Performance Measurements. By K. C. Garner. Pp. x + 204. The Pergamon Press Ltd., 1968. Price (Flexicover) 21s. (Hard Cover) 35s.

The objects of this book are to set out the techniques of dynamic measurements as they apply to control system and component testing, to indicate the reasons for these measurements and to introduce a modicum of the underlying theory to a level sufficient for the purpose and interpretation of these measurements. A large field to encompass in the space of so slim a volume. This is understood, so the book is almost wholly concerned with the performances of linear systems.

This book will be of particular value to postgraduate students and to new graduates in the practical analysis of systems with which they are concerned. It should also be useful to established control engineers who will also find value in this clear and concise summary of current techniques.

After a brief discussion of basic control theory concepts and of the various performance parameters, the first half of the book deals with the equipment used in control system performance measurements. There are separate chapters devoted to transducers, to excitation, to recording and display equipment and to transfer function analysers. The interpretation of trace recordings and of harmonic response diagrams are also dealt with in some detail. The final two chapters are devoted in turn to statistical methods of performance analysis, with a lucid summary of correlation techniques and the power spectrum approach, and to the application of performance measurements to adaptive control systems. There are also three appendixes which should prove useful in practice. A limited number of references is given at the end of each chapter.

Depending on his own knowledge almost every reader will find sections of this book he would like to see expanded, but in so short a book it would be impossible to devote more space to any field and still to maintain balance. Perhaps a discussion could have been included on some of the practical problems encountered in system measurements and more guidance would also have been welcome on the choice of equipment and measuring techniques for systems which include a degree of backlash or which are subjected to noise or unsteadiness.

On the whole the author has achieved his purpose extremely well. The book will prove a sound reference. It is easy to read and should be a stimulus to greater involvement.

J. W. Hargreaves

Reproduction and Man. By R. J. Harrison. Pp. vi + 134. Contemporary Science Paperback 3. Edinburgh & London; Oliver & Boyd, 1967. Price 7s. 6d.

Human populations and the factors controlling reproduction are an intriguing field of study and raise many correlated and conflicting problems, the most publicised of which is the concern at the probability of there being 6000 million people in the world by the year 2000. Will it be possible to produce by that date sufficient food to feed ten times that number (as had been suggested) or will biological regulatory mechanisms, other than wars, come into force. In other species such regulatory mechanisms include "population crashes", decrease in fertility and increase in the number of stillbirths, suppression of natural defence mechanism and the appearance of disease resulting from endocrine stress. Already in man there is disquieting evidence in our highly populated cities of overcrowding syndromes arising, which are probably hormone-linked. And incidentally how much of modern neuroses is linked with the modern emancipation of the female in conflict with the traditional (and genetic ?) dominance by the male ?

Against this background R. J. Harrison deals with the physiology patterns of human reproduction. His book is extremely readable and begins with an interesting and thought-provoking introduction on reproduction in relation to population and the factor which may affect both. The first chapter discusses Patterns of Reproduction in the sense of events in man's reproductive life, such as puberty, adolescence, sexual maturity, pregnancy and fecundity; mammals other than man are also discussed. Following chapters deal with female and male reproductive organs and hormone control, early stages in pregnancy (including development of the embryo), pregnancy, the placenta and birth. There is a brief Synopsis of Reproduction.

Although basically a physiological essay the book should be of value to the non-biologist, as well as the biologist, seeking a survey of the field and is to be recommended. The bibliography is very useful and notes about the books give added value.

The index is quite good and should fulfil the needs of the biological non-specialist as well as the general reader. There is one addition that I would have liked and that is a chapter devoted to the effects of stress and overcrowding on animal reproduction—this would have been an extremely useful addition to an already worthwhile book and would have completed this survey of human reproduction.

D. J. Tighe-Ford

Elements of Marine Ecology. An Introductory Course. By R. V. Tait. Pp. vii + 272. London; Butterworths, 1968. Price 62s.

This book in some respects is difficult to review spanning as it does a very wide range of disciplines but in its aim to provide an aid for zoology students at the start of a special course in marine biology, it is successful. The fact is that it is unique in that it is probably the only book with this precise objective in view. On the whole the treatment of the subject is adequate covering as it does the ocean currents, planktonic organisms, the parameters of the environment, the sea bottom, sea shore and sea fisheries, etc. It would, however, have been beneficial if more extensive coverage had been given to the planktons and mention of the absorption of light of different wave length could have been profitably included in the text. Rather surprisingly no mention is made in the suggestions for further reading, after the chapter on 'Sea Fisheries' of the extensive literature on the work carried out by the continuous plankton recorder survey.

In the field of oceanography and fisheries there is a tremendous amount of international co-operation but this is not mentioned in the book and no reference is made to the important Marine Stations. The development of sea laboratories and submersibles is proceeding at an ever increasing pace, yet the implications of these advances have not been referred to. One would suggest that this subject should be included in any future edition in order to add to the stimulation of the students' interest. However, despite these limitations this book is a reasonable introduction to the subject of Marine Ecology.

D. R. Houghton

Cybernetics and Management. By Stafford Beer. Pp. xii + 240. London; The English Universities Press Ltd., 1967. Price 21s.

This is the second edition of a book in the E.U.P. Management Science series. Those who have read Stafford Beer's "Decision and Control" or his other contributions in the fields of operational research and cybernetics will either accept his style as eminently readable or condemn it as science for the businessman. This contretemps is immediately apparent. In the first part of the book, which describes systems and control mechanisms, we are reminded that a pair of scissors is a system which can be broken down into another "system of metallurgical components all interacting in special ways." Later in the same section some simple mathematics on the relation between feedback and memory concludes with an apology for not introducing quantum mechanics and a mention of a theory of halucinations! However, this part contains much definitive matter and it is a pity that Part II is devoted to justifiying cybernetics as a science and tracing its history from an "ancient pedigree of thinking." The Logical Theory of Cybernetics, as this part is titled, would have been better as an appendix though the few pages on Boolean algebra, Russell's Theory of Types, Brouwer's Intuistic Logic and Skolen's Recursive Arithmetic would merit an appendix of their own.

Part III is considerably more practical and deals with the achievement of and problems for cyberneticians, including what Stafford Beer sees as a main target—the design of a cybernetic factory. Part IV, The Analogue Theory of Cybernetics, continues to explore possible applications. The last (new) chapter looks briefly at progress in applying cybernetics to management during the last decade and unfortunately reverts to more specious phraseology.

The problem with this book is to decide what audience it will attract. The scientifically inclined businessman or administrator might be fascinated, even though shuddering at the concept of "Constrained Markovian Randomisers" controlling their organisations via "Homeostatic Ultrastability Loops" Those in or on the fringe of science management may get interest, pleasure and some ideas from this book—one to borrow from the library.

M. Hillier

Molecular Biophysics. By D. Chapman and R. B. Leslie. Pp. vi + 151. Contemporary Science Paperbacks 4. Edinburgh & London; Oliver & Boyd, 1967. Price 7s. 6d.

Molecular Biophysics is an interdisciplinary field of study linking biological phenomena at cellular level with the physical and chemical properties of molecules in biological systems. The authors have provided an interesting and coherent introduction to the subject for the non-specialist and have emphasised the essence of life—that living organisms demand a high degree of structural organization and that this involves the continual input of large amounts of energy. The treatment is logical and although treatment in depth is impossible in a book of this size the authors have done a remarkably good job of providing an introduction for the general reader. The following topics are covered: the molecules of biophysics, physical techniques used in their investigation, cell structure and organization, cell energy relationships, and selected topics such as vision, transmission of nervous impulses, muscle contraction, photosynthesis, functions of mitochondria (cell "factories") and bioluminiscence. The text-figures on the whole are poor and not always adequately explained in the text for the general reader. A useful bibliography is given and the index is more than adequate for an introductory book. In summary, this book is to be recommended to those who would like to have a broad view of the subject at an inexpensive price and should be of interest to a wide variety of scientists. For those who would like a greater study in depth the reviewer would suggest as a companion book "Introduction to Molecular Biology" by Haggis *et al.* (given in the bibliography).

D. J. Tighe-Ford

Chemical Exchanges in Man. By B. F. Matthews. Pp. vii + 136. Contemporary Science Paperbacks 10. Edinburgh & London; Oliver & Boyd, 1967. Price 7s. 6d.

The book provides a coherent and logical survey of the physiology of the chemical exchanges occurring in man; its theme being not only what exchanges occur where in man, but also how they occur. Although the size of the book does not permit a detailed study the following topics are well covered: the exchange of carbon dioxide and oxygen throughout the body, the role of the lungs and blood and the chemical control of gas exchange, capillary and tissue exchanges, kidney function and its relation to body pH and osmotic pressure, the role of hormones in the control of sodium and the volume of body fluids. Throughout the author treats the field as a coherent whole, demonstrating the principles common to chemical exchanges in man; wherein lies much of the value of the book. The bibliography gives references for groups of chapters and would be of use to the biologist rather than the general reader. The index is adequate for the non-specialist readership for which the book was intended.

Although the book is intended primarily for biologists, the non-biologist will find much to attract his interest and is to be generally recommended.

D. J. Tighe-Ford

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Authors are requested particularly to note that as the JOURNAL is in the Restricted category the printing of material within its pages does not constitute open publication and does not prejudice the subsequent use of the material in the journal of a learned Society or Institution, or in the scientific and technical press.

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Illustrations are in most cases a desirable addition. Photographs should be of good quality, glossy, unmounted, and preferably between two and three times the size of the required final picture. Graphs and line drawings should be made on a similar large scale, with bold lines to permit reduction in block making.

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